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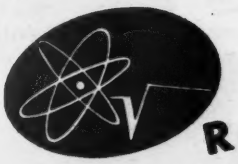

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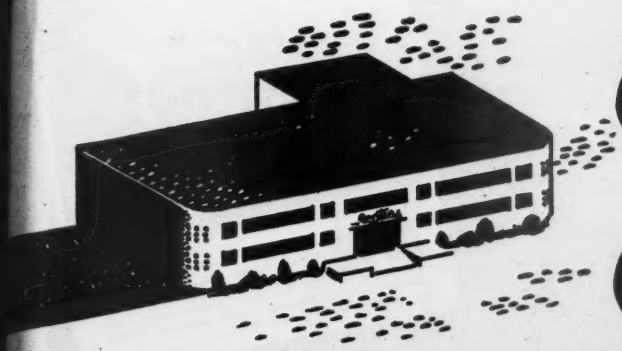

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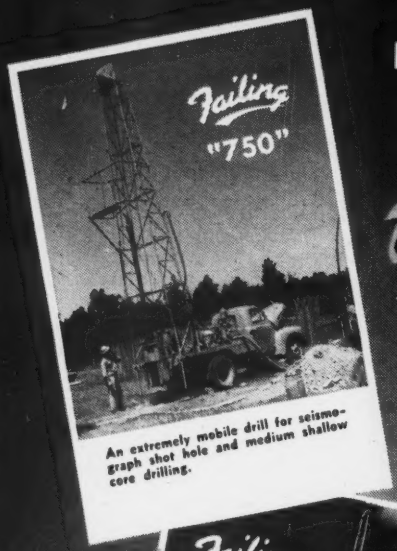

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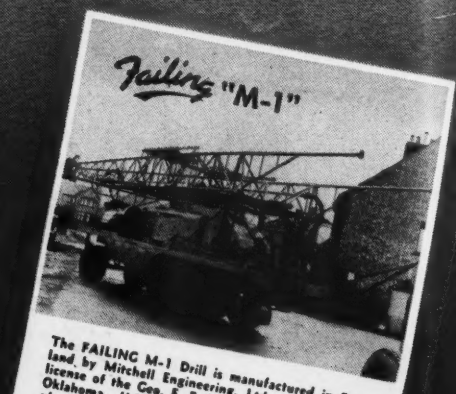

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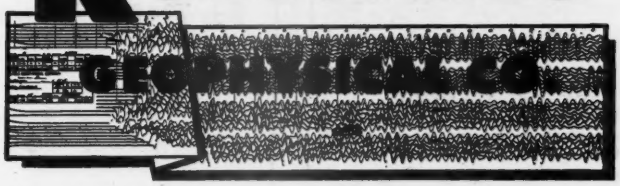

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1. Entries, to qualify, must be received at the business office of the Society of Exploration Geophysicists, Box 7248, Tulsa, 18, Oklahoma, on or before March 1, 1951. Only active, associate or student members in good standing of the Society of Exploration Geophysicists shall be eligible to enter. Current officers and members of the Standing Committee on Honors and Awards are not eligible to receive prizes.

2. Line drawings must be made with India ink on plain white paper or on tracing cloth. Lettering, if used, must be of sufficient size to be legible after reduction. Designs shall be judged on simplicity and clarity of meaning. They may be of any geometric form considered practical for use in the embellishment of award certificates, plaques, corporate seal or society letterhead. As a guide to the general nature of suitable designs, your attention is invited to the official crests of other societies, such as Geological Society of America, American Geophysical Union, American Institute of Metallurgical Engineers, Houston Geological Society etc., or the designs used by some of the geophysical companies whose advertisements appear in *Geophysics*.

3. The Standing Committee on Honors and Awards shall be the sole judges. All entries shall become the property of the Society of Exploration Geophysicists and cannot be returned to contestants. In the event no design is chosen, the Society reserves the right to extend the contest.

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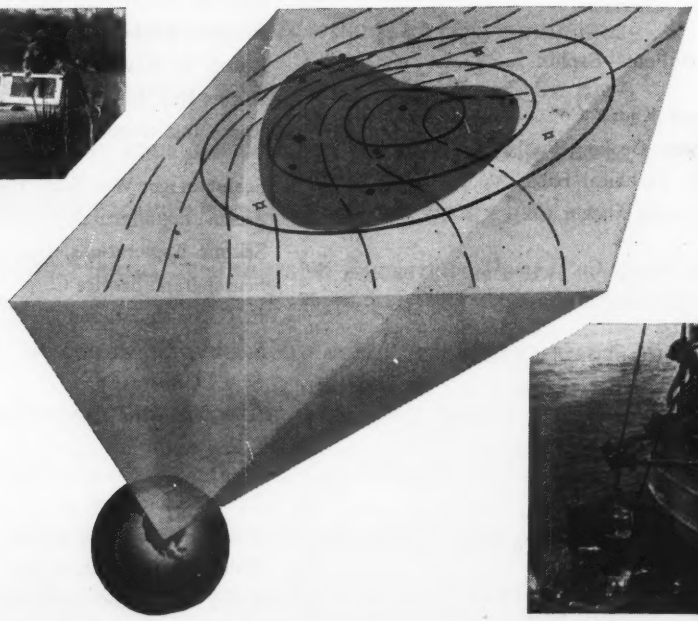

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THE FORT COBB ANTICLINE

A GEOPHYSICAL CASE HISTORY*

FRANCIS F. CAMPBELL†

ABSTRACT

The Fort Cobb anticline is in T-8-N, R-12-W, Caddo County, Oklahoma. Its history is one of geophysical success and commercial failure. Amerada Petroleum Corporation found seismic evidence of a large closed structure and drilled a 10,000 foot dry hole on top of it. Then The Superior Oil Company shot the area and drilled two more tests. The first Superior test was drilled to 17,800 feet and was the deepest test in the world at the time. The presentation of data includes reproductions of seismic records, cross-sections, and structure maps on three horizons.

INTRODUCTION

The regional setting of the Fort Cobb area in southwestern Oklahoma is shown in Figure 1. Contours on top of the Deese (Des Moines) outline the southeast part of the Anadarko basin and show that the Fort Cobb area is near the axis of the geosyncline. Cement and Apache are the nearest oil fields. When operations described in this case history began in 1940, Cement was well established as a producing field and the discovery well was being drilled at Apache.

Amerada Petroleum Corporation discovered the Fort Cobb anticline in T-8-N, R-12-W as the result of a reconnaissance seismic program and drilled Amerada No. 1 Sprague on top of the structure to a depth of 10,231 feet. Then The Superior Oil Company of California shot the area and drilled two more tests on it. The first of these was the Superior No. 1 Weller which was drilled to 17,823 feet. At the time it was the deepest drilling operation in the world.

The geophysical case history of the Fort Cobb anticline presents records, cross-sections, and structure maps from Amerada and Superior. The seismic techniques may be compared, and since there is only a limited amount of well control to confirm the presence of the anticline, the correspondence of the results is one of the best proofs of the validity of the seismic data.

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† Amerada Petroleum Corporation, Tulsa, Oklahoma.

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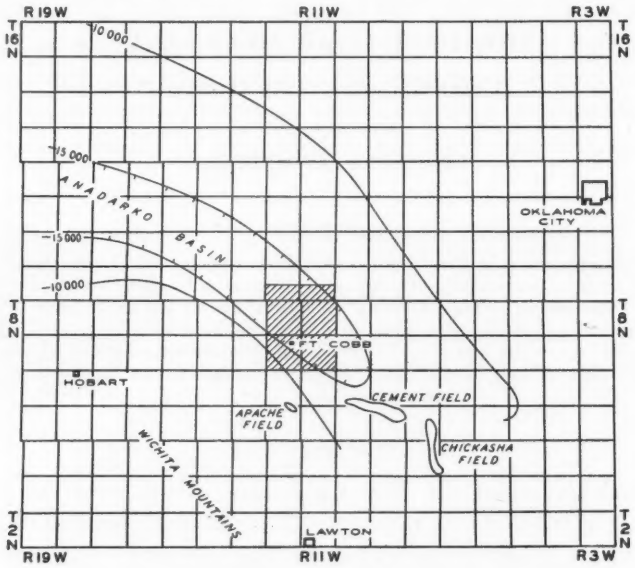

FIG. 1. Regional setting of Ft. Cobb area in Southwestern Oklahoma. Contours on top of Deese.

After an initial comparison of an Amerada record and a Superior record the order of presentation of the data is chronological. Except for the Amerada cross-sections the method of presentation is the same as the original interpretation of the data.

Comparison of Amerada and Superior Techniques

Figure 2 shows an Amerada record above a Superior record. The records were shot at almost precisely the same place in the Fort Cobb area. They are aligned on the best reflection which arrives at 1.4 seconds. This reflection comes from the upper part of the Hoxbar section of Missouri age. The Amerada structural in-

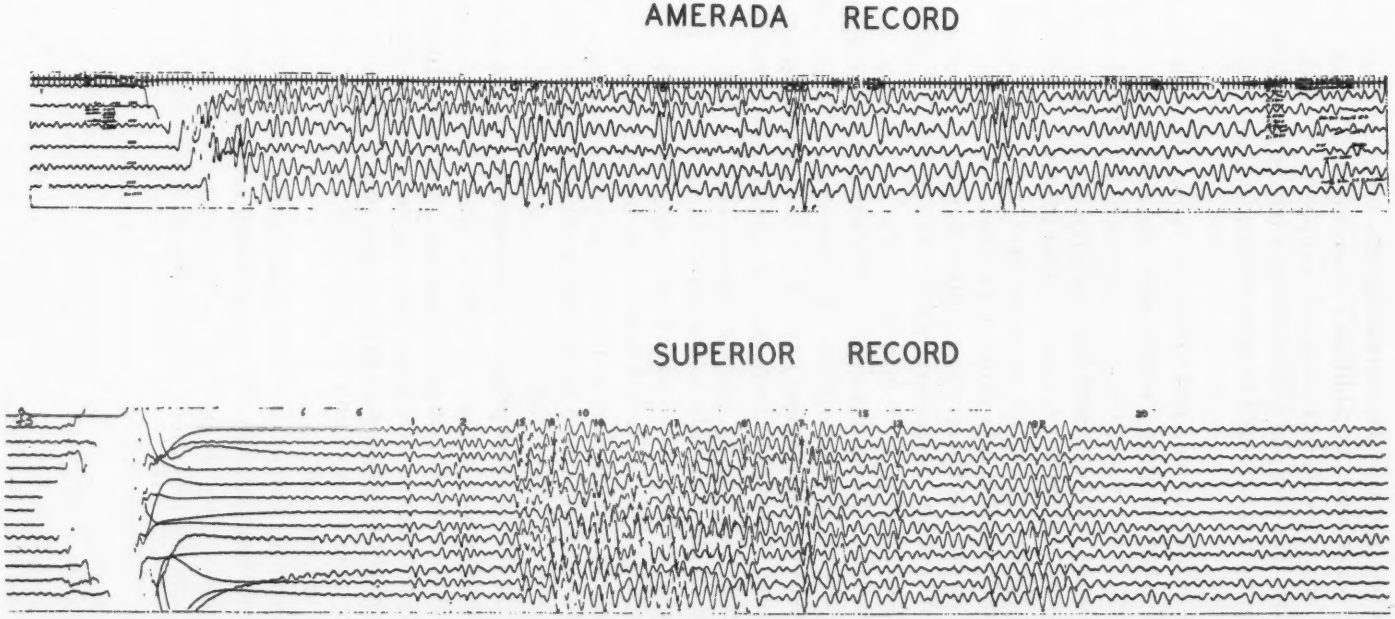

FIG. 2. Comparison of Amerada and Superior records.
Location: west side of section 24, T-8-N, R-12-W.

terpretation depends primarily on correlating this reflection from one place to another over the whole area. In addition a shallower pick at 0.9 second and a deeper pick at 1.8 seconds were correlated and mapped by Amerada. The Superior structural interpretation also places chief reliance on the Hoxbar reflection, but the Superior program was arranged to give continuous control rather than spot correlation.

The Amerada record was obtained with six recording channels. The top trace is at a distance of 1,000 feet from the shot point and the bottom trace 2,000 feet from the shot point. A single geophone was used on each channel, no mixing was used, and an automatic volume control was employed in the amplifier. The over-all frequency response of the geophone, amplifier, and galvanometer was peaked between 40 and 75 cycles per second at 70 per cent of maximum response. The charge of 15 pounds was shot at a depth of 115 feet.

The Superior record has thirteen recording channels. The top trace is 1,200 feet north of the shot point, the center trace is at the shot point, and the bottom trace is 1,200 feet south of it. Four geophones were connected in series to each channel with a separation between geophones of fifteen feet. The channels are not mixed. The over-all frequency response was somewhat broader than for the Amerada record with the low frequency cut off of the amplifier near 30 cycles per second at 70 per cent of maximum response. The amplitude was controlled by an expander which was triggered by the first breaks. The first breaks are "up" in contrast to those on the Amerada record which break "down." The Superior record was shot with a charge of 10 pounds at a depth of 90 feet.

In the Amerada program a record next to the one shown was obtained by shooting at a location 1,000 feet or more from the geophone position of the bottom trace and with the same recording setup, and another record by shooting to a recording setup on the opposite side of the shot point from which the record shown was taken. In the Superior program there were shot points at the location of the top and bottom traces of the record shown, and the next record would be obtained after moving one half the geophones and cable around the other half. Thus the Amerada shot points were 3,000 feet or more apart and the control on a reflecting horizon might be 30 per cent of the length of profile line on the surface. The Superior shot points were 1,200 feet apart and the control on a reflecting horizon might be 100 per cent.

The differences in the two seismic techniques should be borne in mind while considering the following data. In the writer's opinion the use of multiple geophones is the difference in technique which accounts for most of the improvement in quality of the Superior reflections over the Amerada reflections.

Amerada Data

The Amerada data is presented on three structure maps of the Fort Cobb area, on two cross-sections, and on reproductions of two groups of records. The structure in the Pontotoc (Wolfcamp) is shown in Figure 3, the structure on top

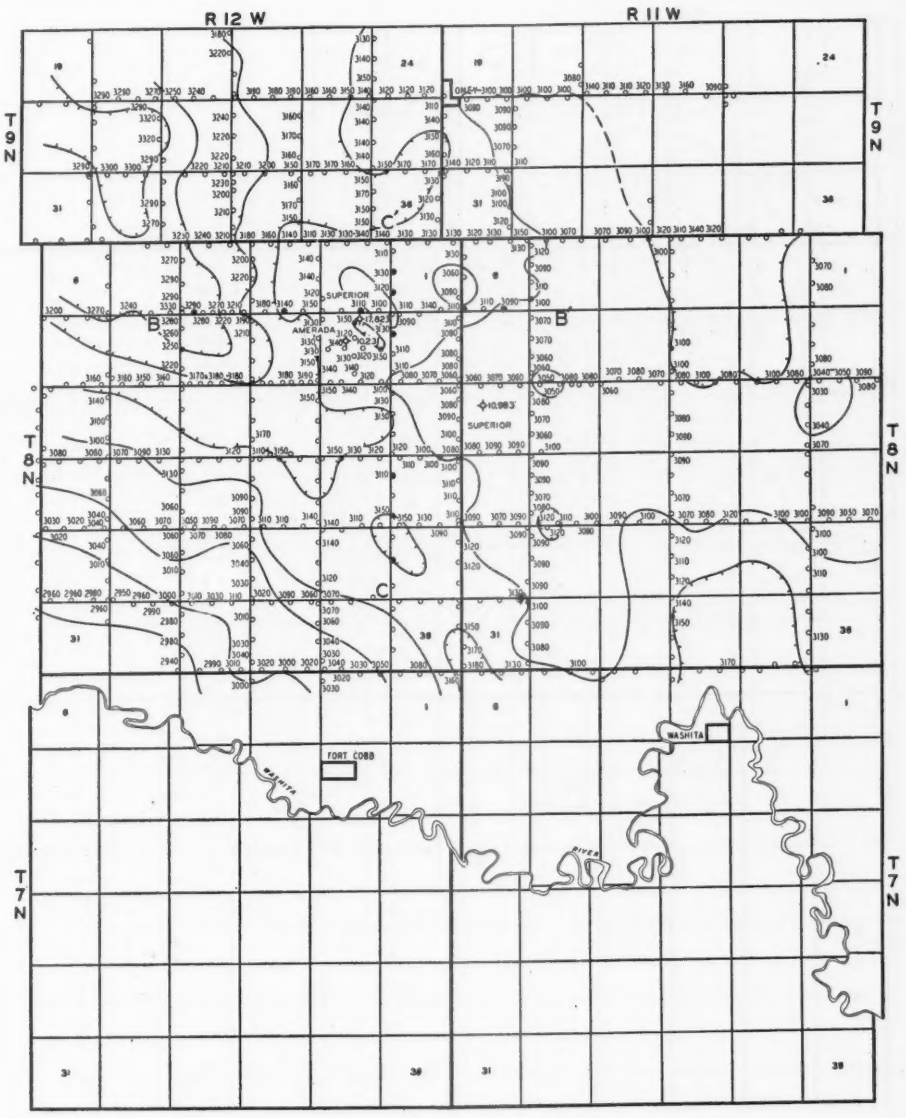

FIG. 3. Structure in Pontotoc (Wolfcamp), Ft. Cobb area, Amerada correlated reflection data.

of the Hoxbar (Missouri) in Figure 4, and the structure about the top of the Deese (Des Moines) in Figure 5. The contour interval on all these maps is 50 feet. The location of the cross-sections are marked *BB'* and *CC'* on the maps. Cross section *BB'* is illustrated in Figure 6 and a group of five records taken along this line are presented in Figure 7. Cross section *CC'* is shown in Figure 8 and records along it in Figure 9. The solid black circles on the maps mark the location of the records which are reproduced.

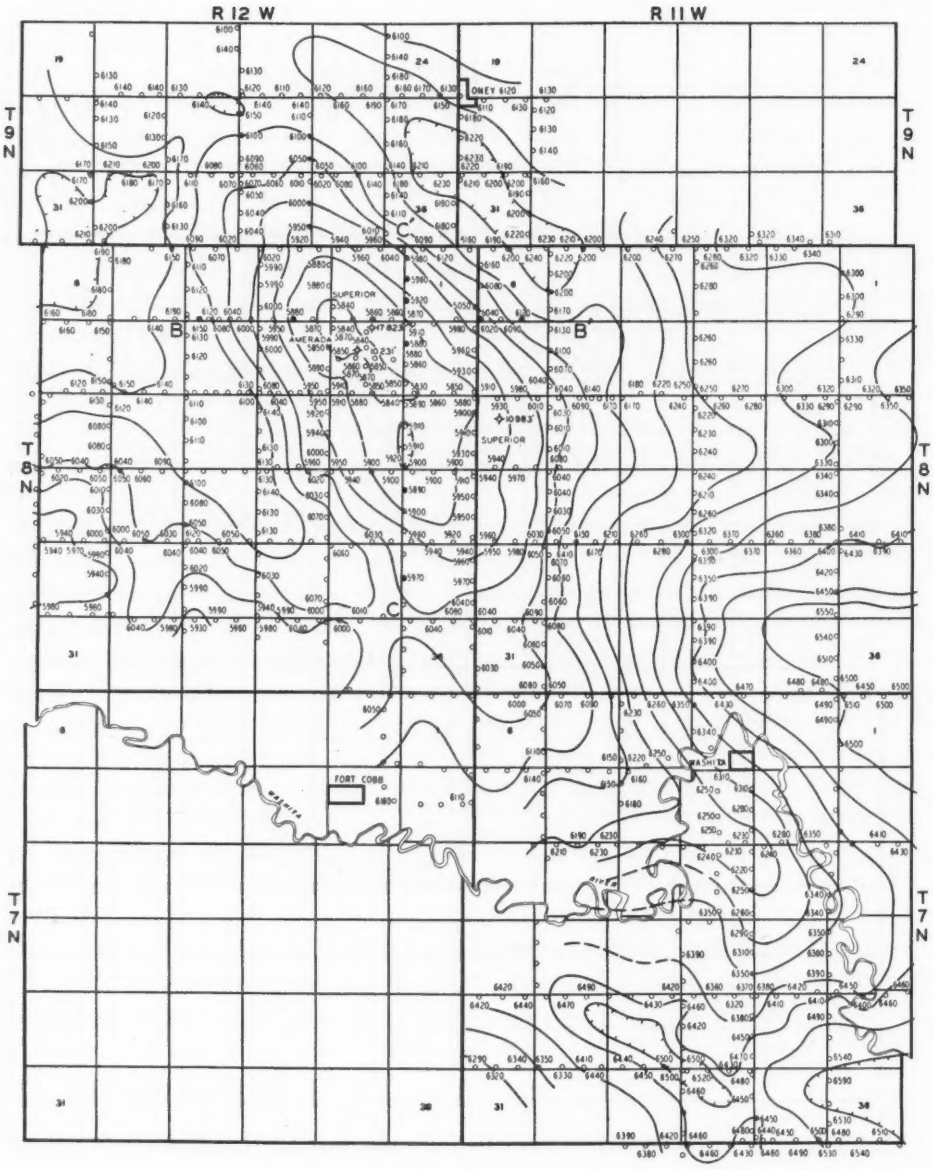

FIG. 4. Structure on top of Hoxbar (Missouri), Ft. Cobb area, Amerada correlated reflection data.

More than five hundred seismic records were obtained by Amerada in the Fort Cobb area. Because of the limitations of space only ten are reproduced here. These ten were selected along *BB'* and *CC'* which intersect near the apex of the structure and on which both Amerada and Superior data are available. Although it is believed that the ten records are typical of those along these two lines, they

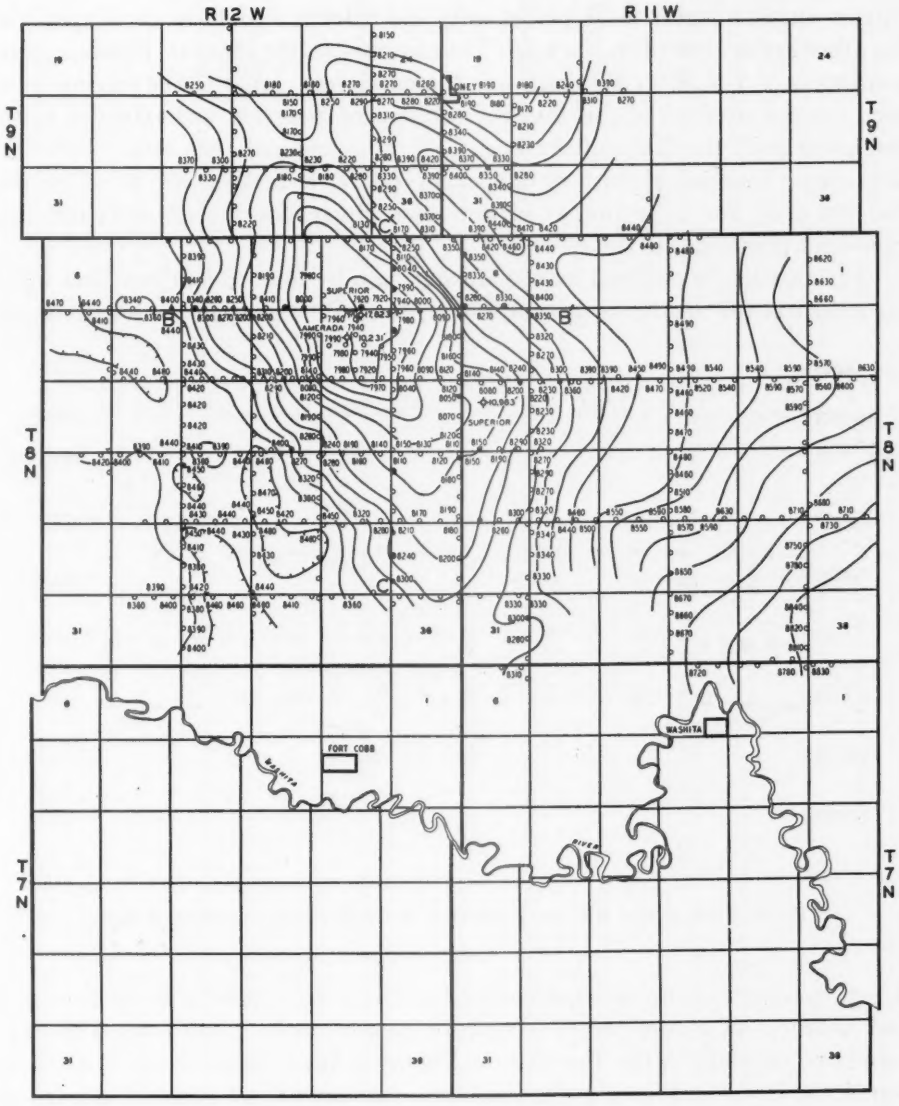

FIG. 5. Structure about top of Deese (Des Moines), Ft. Cobb area, Amerada correlated reflection data.

are an inadequate sample of all the data. The best quality reflections were obtained on the southeast part of the structure.

The exploratory seismic survey which resulted in the discovery of the Fort Cobb anticline began in 1940 as a reconnaissance program in T-5, -6, and -7-N, and R-9, -10, and -11-W. This area surrounds the Cement oil field. A gridwork of control forming squares two miles on a side was laid out on section lines. The circles on the maps mark depth control points and show the shooting pattern.

Circles without depths mark places where no reflection could be correlated with the other depth control on the map. The contours on the Hoxbar, Figure 4, show a nosing in T-7-N, R-11-W which was the northwest corner of the original prospect. On the strength of this lead the exploration program was extended to the northwest until the limits of the Fort Cobb anticline had been established. The most dense shooting pattern developed in T-8-N, R-12-W where every section line was shot, and in section 11 of this township several records were obtained from shot points inside the section.

The anticline is outlined on the Hoxbar map by four 50 foot contours which are closed in the northeast part of T-8-N, R-12-W. The highest closed contour

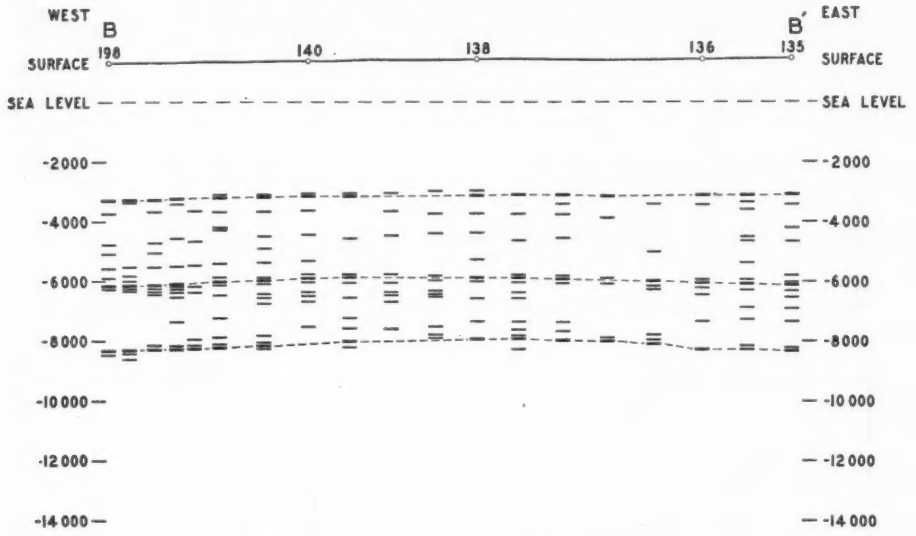

FIG. 6. Cross section BB′, Ft. Cobb area, Amerada correlated reflection data.

is −5,850 and it centers around section 11. The lowest closed contour is −6,000 and embraces an area of twelve sections or approximately 7,500 acres. The structure is not evident in the Pontotoc in Figure 3, but is more pronounced in the top of the Deese in Figure 5. On the Deese map six 50 foot contours are closed, and more might be closed if control had been obtained in T-7-N where the Deese reflection could not be correlated. The apex of the structure on the Deese map in section 11 is slightly east of the apex on the Hoxbar map. The axis of the structure is N 25° W. in the Deese compared to N 30° W. in the Hoxbar.

Cross sections *BB′* and *CC′* intersect at the northeast corner of section 11 near the apex of the anticline. The cross sections were prepared especially for this case history and were not included in the original interpretation. They show the persistence of reflection horizons and the variation of structure with depth which would be demonstrated more fully by the reproduction of all the records on the

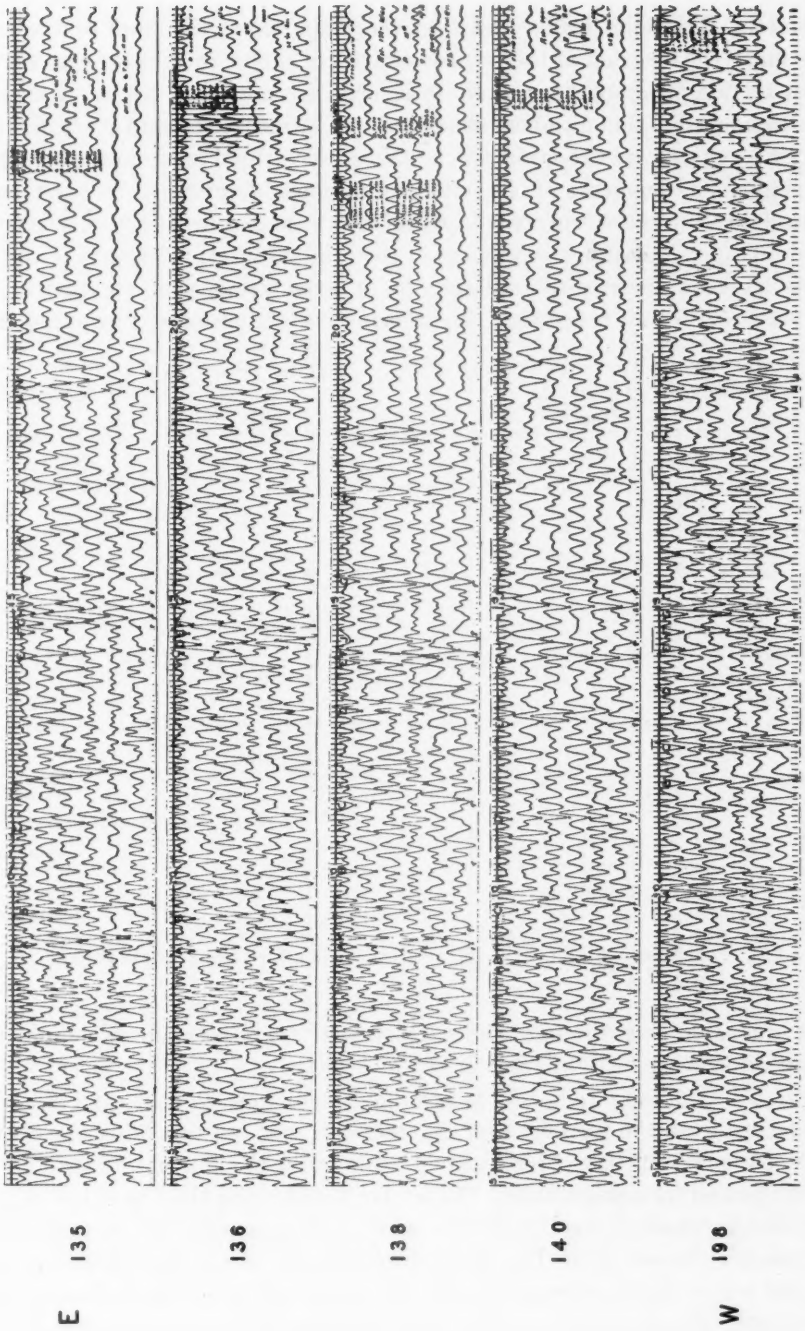

FIG. 7. Amerada data for cross section on BB' line.

cross sections. The solid black circles on the maps along the lines of the cross sections mark the location of the records which are shown in Figures 7 and 9. On the cross sections the positions of these records are noted by circles at the top with profile identification numbers above them. The horizontal and vertical scales on the cross sections are the same which makes the vertical relief on the structure appear slight. The segments of the reflection horizons determined by the records are plotted directly below the control points. Since the segments are only 500 feet long and no dip calculations were made in the original interpretation, the control segments have not been displaced for dip. A fixed velocity of 10,450 feet per second was used for all reflections. Weathering corrections were computed from

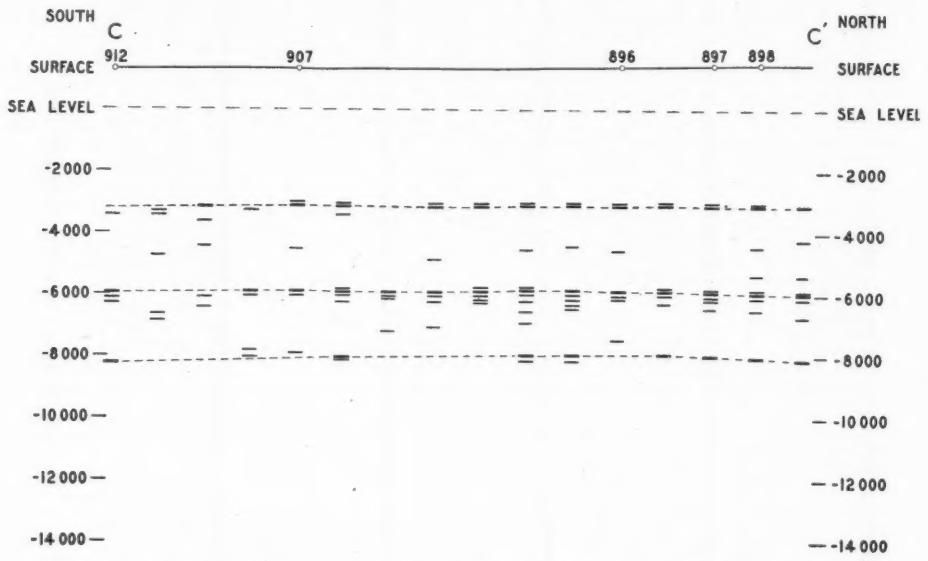

FIG. 8. Cross section CC′, Ft. Cobb area, Amerada correlated reflection data.

the first breaks on "weathering" shots which were taken at each shot point and recording setup with small charges in shallow holes.

Figure 6 for cross section *BB′* is arranged from west to east, and Figure 7 has the record from the furthest east control point, 135, on top. Only the central portions of the records have been reproduced in order to show more detail on the reflections picked for computation. The letters noted along the top of the records serve to identify these picks. Usually the sequence begins with "A" on each record and proceeds alphabetically. The black dots indicate where the reflections were picked and which traces were included in the computation. In the following table the correlated reflections are noted by identification letter and sub-sea depth for each of the three map levels:

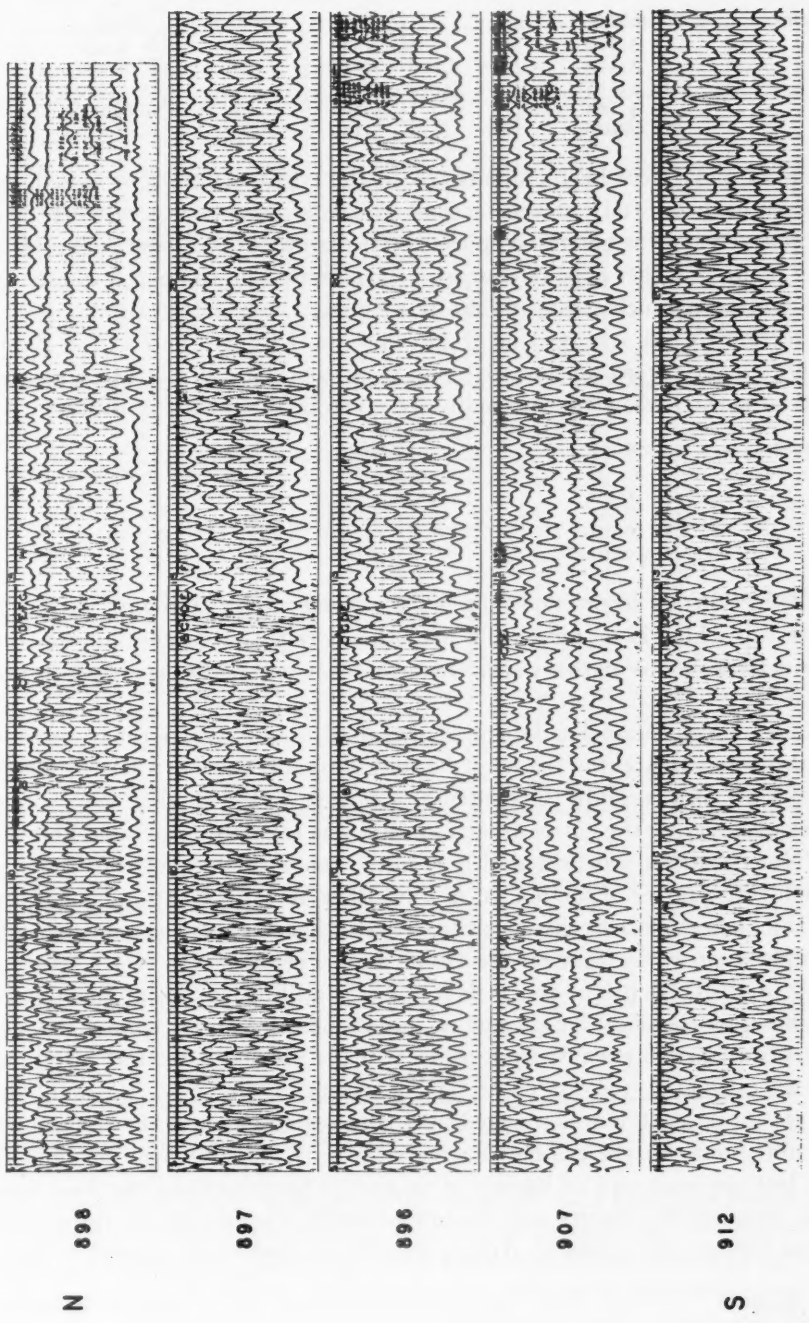

FIG. 9. Amerada records for cross section on line CC'.

Control Point	*Pontotoc*	*Hoxbar*	*Deese*
135	A 3,090	G 6,120	N 8,330
136	A 3,110	D 6,040	I 8,280
138	K 3,110	F 5,860	I 7,920
140	B 3,140	G 5,880	No control
198	No control	F 6,150	I 8,340

The correlated picks have been emphasized on the cross-sections and have been connected by dashes. Study of the records reveals several instances where the reflection character of the correlated picks is not distinct. The Deese pick on 136 is a case in point. Another type of character variation is shown on 198 where the G pick at −6,300 is much stronger than the F pick which is correlated.

Cross section *CC'* is arranged on Figure 8 with the north end at the right, and in Figure 9 the record at the north end is on top. The correlated picks and their depths for the three structure maps are given in the following table:

Control Point	*Pontotoc*	*Hoxbar*	*Deese*
898	J 3,130	E 5,960	K 8,040
897	I 3,120	C 5,920	G 7,990
896	H 3,130	C 5,880	No control
907	No control	D 5,890	No control
913	No control	C 5,970	G 8,240

The deep reflections on record 898 show an abnormal rate of step out. This indicates north dip which is in agreement with the closely spaced contours on the Hoxbar and Deese maps at this point. The record at 907 is the Amerada record in Figure 2.

The Amerada interpretation depended principally on the Hoxbar map because the structure is not apparent in the Pontotoc and the quality of control in the Deese is much inferior. As a result of the evidence of closure on the Hoxbar map a solid block of leases covering the entire area of closure was taken by Amerada, and the Amerada No. 1 Sprague was drilled in 1941 in the center of the southeast quarter of the northwest quarter of section 11, T-8-N, R-12-W. This location is near the center of the highest closed contour on the Hoxbar map, Figure 4, and just outside the highest closed contour on the Deese map, Figure 5. The No. 1 Sprague was drilled to a total depth of 10,231 feet and was still in Hoxbar at this depth. The Schlumberger electrical log showed no indications of porosity from 7,300 feet to total depth. A drill stem test from 9,435 to 9,492 yielded 2,050 feet of oil cut mud and an estimated 300,000 cubic feet of gas per hour. After the well was drilled to its total depth it was plugged back and tested again in the same zone. During a nine hour test the gas flow decreased from 2,250 cubic feet per hour to 700 cubic feet per hour and 18 barrels of oil and 38 barrels of gas cut mud were recovered. The lack of porosity and the low permeability throughout the section discouraged further operations by Amerada and the leases were dropped in 1942.

Superior Data

The Superior data is presented on two structure maps of the Fort Cobb area, on two cross sections, and on reproductions of two groups of records. The manner

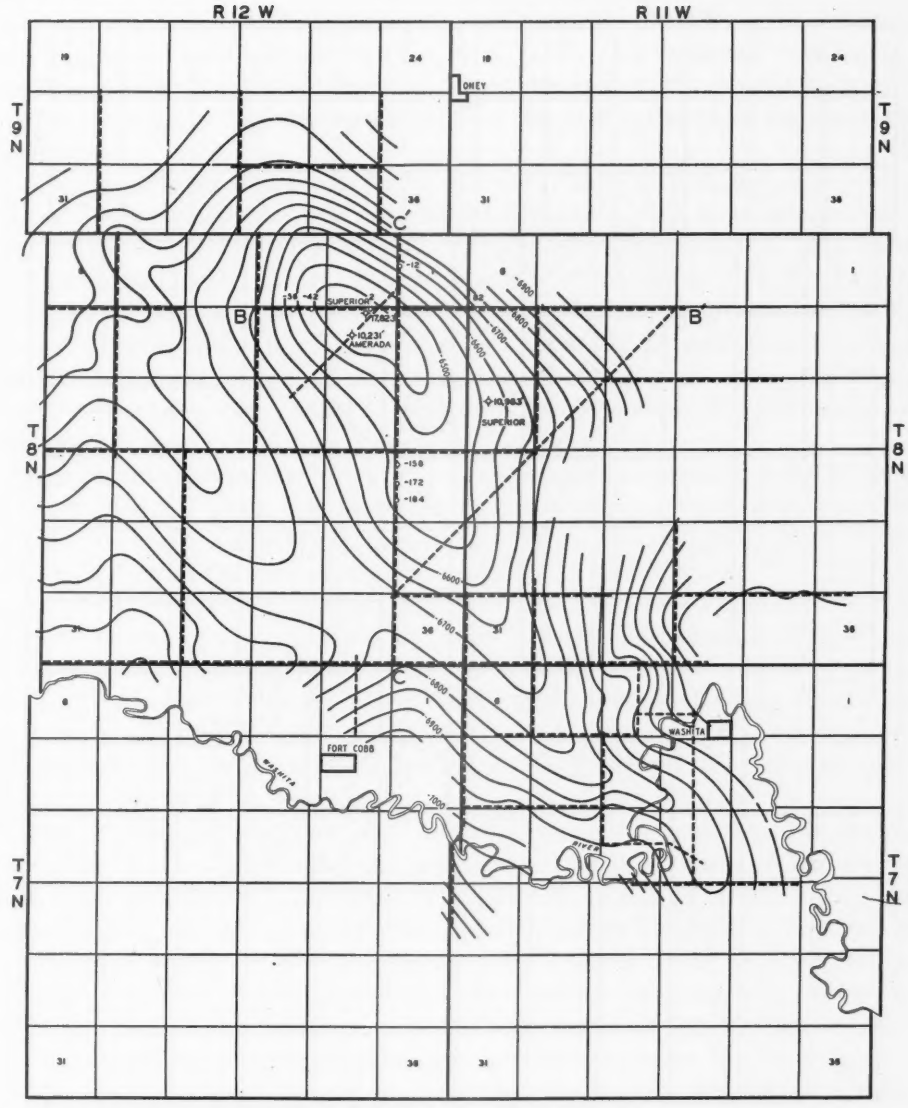

FIG. 10. Structure on top of Hoxbar (Missouri), Ft. Cobb area, Superior continuous reflection data.

of presentation is the same as for the Amerada data except as noted. The structure on top of the Hoxbar is shown in Figure 10 with a 50 foot contour interval, and the structure about the top of the Deese is shown in Figure 11 with a 100 foot contour interval. Cross section *BB'* and a group of four records along it are presented in Figures 12 and 13, and cross section *CC'* and a group of records along it in Figures 14 and 15. Only eight Superior records out of some 400 in the area have been reproduced.

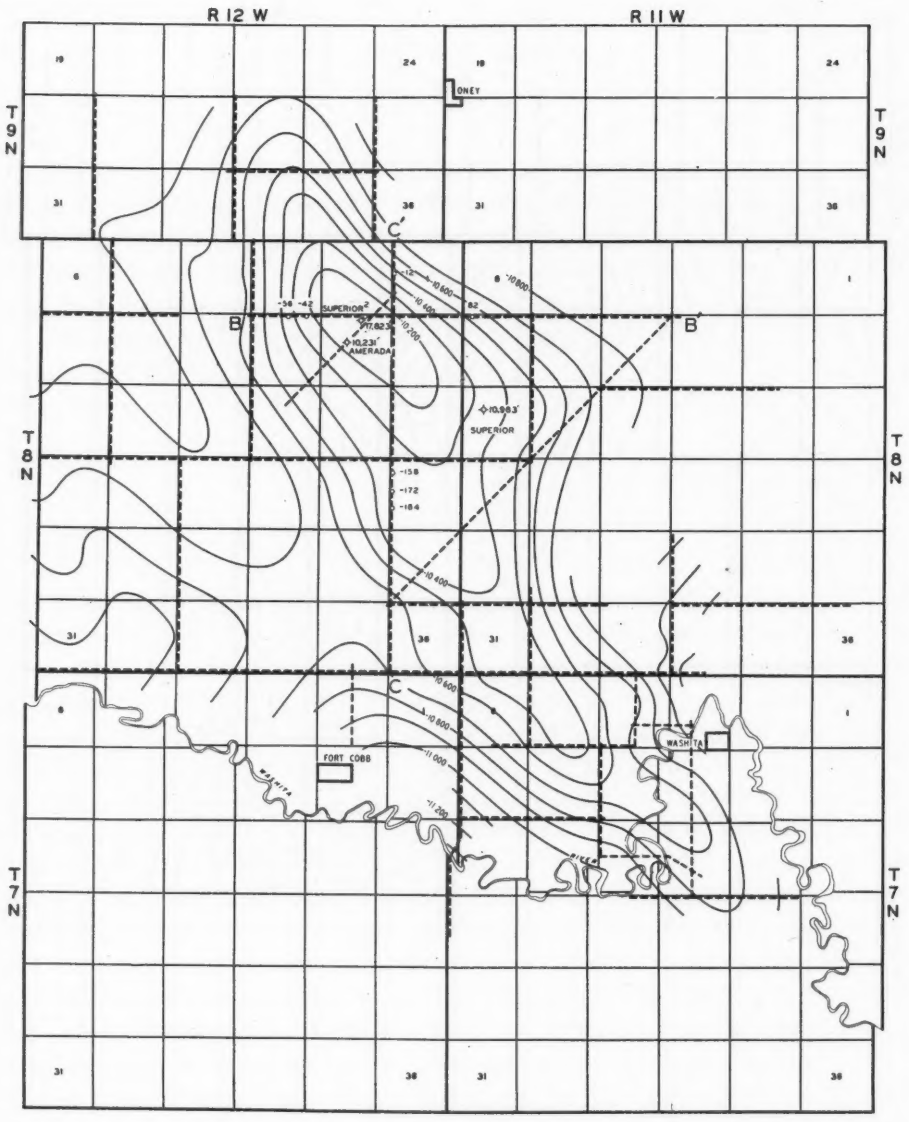

FIG. 11. Structure about top of Deese (Des Moines), Ft. Cobb area, Superior Phantom Horizon.

Early in 1944 Superior took a shooting option on the block of leases previously held by Amerada and moved a seismic party into the area before the end of the year. The dashed lines on the Superior maps show the shooting pattern. Shot points were located every 1,200 feet along these lines and recording setups were arranged across the shot points to give continuous sub-surface control. The program started with a northeast-southwest line across the Amerada No. 1 Sprague and continued with an irregular gridwork of lines of approximately the

same pattern as the Amerada reconnaissance program. The axis of the structure was followed to the southeast into T-7-N, R-11-W. This extension went beyond the limits of the shooting option, so additional leases were taken while the shooting was in progress. The most dense Superior shooting pattern is in the southeast extension.

The Superior structure map on the Hoxbar, Figure 10, is based on the same outstanding reflection that was correlated by Amerada. The cross-sections show that control on this horizon was obtained on almost every record. The Fort Cobb anticline is outlined by the six 50-foot contours which are closed. The highest one, −6,450, embraces a slightly larger area than the highest closed contour on the Amerada Hoxbar map. The lowest closed contour on the Superior map is −6,700 but whether or not to close it on the southwest flank is a matter of choice by the interpreter. The −6,650 contour corresponds with the lowest closed contour on the Amerada map.

The Superior Deese map, Figure 11, is not based on correlated data but on a phantom horizon which was projected on the cross-sections according to the nearest data above and below it. The Superior Deese map also differs from all the other maps in that the contour interval is 100 feet instead of 50 feet. The anticline is outlined by five of these 100 foot contours which are closed. The area of closure extends into the northwest corner of T-7-N, R-11-W. The Amerada Deese map does not show such a large area of closure because no control was obtained south of T-8-N. The contour level of the Amerada Deese map is some 2,000 feet shallower than that of the Superior Deese map. A greater velocity was used for the Superior data, so the actual difference in depth of control is closer to 1,000 feet or 0.2 second on the records.

The Superior cross-sections *BB′* and *CC′* are in the same position as the Amerada cross-sections. The open circles along these lines with numbers above them mark the location of records shown in Figures 13 and 15 on which they are similarly identified. The numbers represent distances in hundreds of feet from a zero reference point. On *BB′* the reference point is at the center of the north line of section 11, T-8-N, R-12-W, and records are shown for stations +82, +2, −42, and −56. On *CC′* the reference point is at the north end of the line and the records for stations −12, −158, −172, and −184 are shown.

The control segments plotted on the cross-sections are 1,200 feet long. They are displaced according to the dip. The depth depends on a linear velocity function. Both differential and absolute weathering corrections were computed from the first breaks. The reflections are identified by a system of numbers and letters near the top of the records which are the same for a particular reflecting bed over the whole prospect. Thus 7 identifies the reflection which is used for control on the Hoxbar map. The control segments for this pick have been emphasized on the cross-sections. In general the shallow picks have low identification numbers and the deep picks have high numbers. Picks which vary from an established pick by only a leg are designated by a "*z*" or an "*x*" following the number. Thus pick 1

is the next to the highest one on cross-section *BB'* and *CC'* and it has been picked on all but one record on these lines. The level of the Deese phantom horizon is indicated by short, heavy dashes on the cross-sections. On *BB'* it is controlled by pick 9 on the east end of the line, and pick 15 on the west end of the line. On the north end of *CC'* pick 9 has been correlated and plotted 500 feet above the phantom. On the south end the preceding leg, pick 9*a*, controls the phantom.

Superior Drilling

The seismic evidence of an anticline with 400 feet of closure at the top of the Deese and the intensified search for crude reserves following the war led Superior

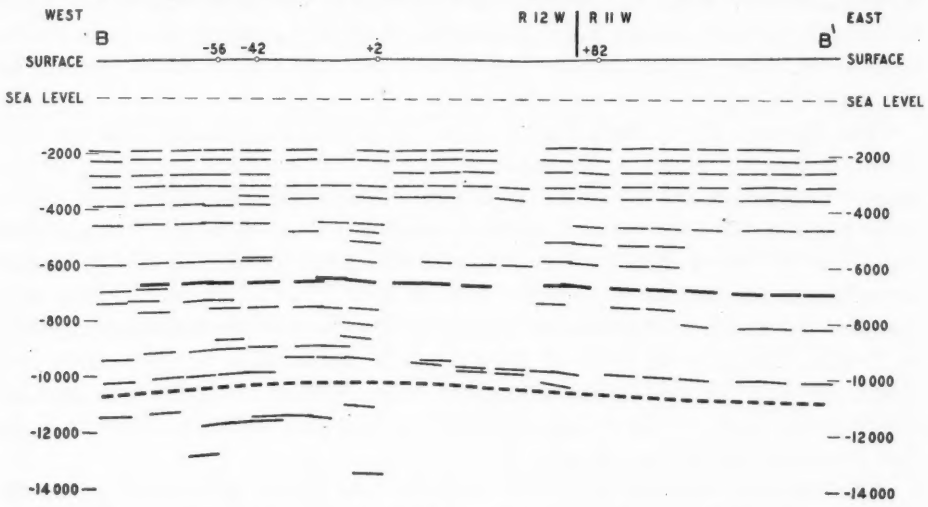

FIG. 12. Cross section BB', Ft. Cobb area, Superior continuous reflection data.

to begin drilling the No. 1 Weller in 1946. The location is in section 11 about 2,000 feet north and a little east of the Amerada No. 1 Sprague. The No. 1 Weller was drilled to 17,823 feet and was still in the Springer formation (Morrow) of the lower Pennsylvanian at total depth. Several slight shows of oil and gas were encountered in the lower Hoxbar, Deese, Dornick Hills, and Springer, but none offered any promise of profitable completion of the well. A discussion of the geological data from the No. 1 Weller has been published by Wheeler and Wallace (1949).

In 1949 the Superior No. 1 Cogdill was drilled on the east flank of the anticline in section 18, T-8-N, R-11-W. It was dry and abandoned at 10,983 feet in lower Hoxbar. In connection with the location of this test attention is called to the Amerada Deese map. The control points immediately north and west of the Superior No. 1 Cogdill have sub-sea data of 8,080 and 8,050 respectively. These points were ignored in the contouring, but if they are used rigorously, a small area of closure could be shown around this location.

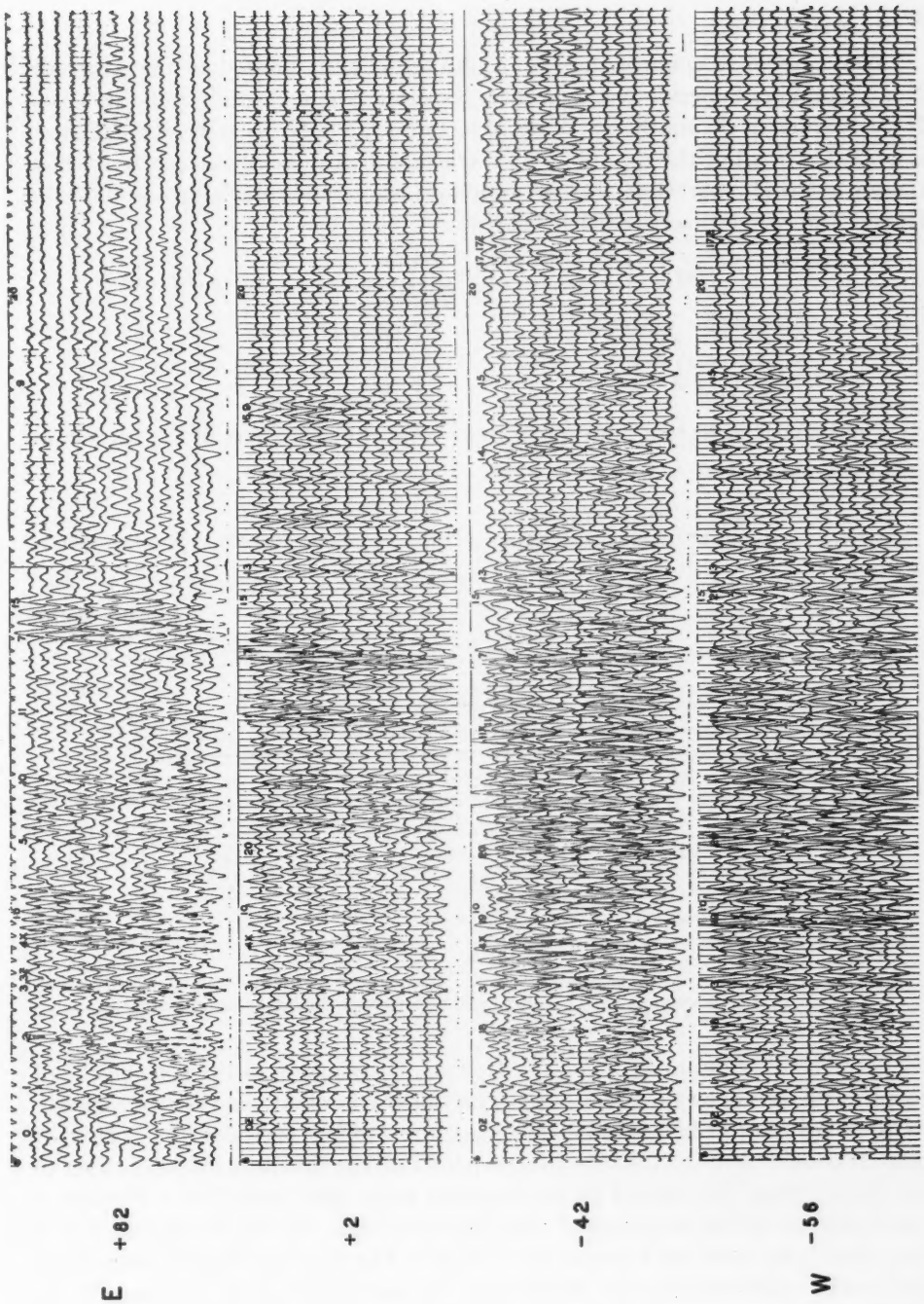

FIG. 13. Superior records for cross section on line BB'.

Well Confirmation

Well control to confirm the Fort Cobb anticline is limited to the Amerada No. 1 Sprague, Superior No. 1 Weller, Superior No. 1 Cogdill, and the Texas No. 1 Warden in the southeast corner of section 17, T-8-N, R-10-W. A correlation is available in all of these tests on an ostracodal limestone about 400 feet below the top of the Hoxbar. Only the two Superior tests can be correlated on top of the Deese. The correlations are listed below:

Well	*Hoxbar Ostracodal Limestone*	*Top of Deese*
Amerada No. 1 Sprague	−6,099	
Superior No. 1 Weller	−6,118	−9,173
Superior No. 1 Cogdill	−6,253	−9,392
Texas No. 1 Warden	−6,890	

The Hoxbar reflection appears to come from the same part of the section as

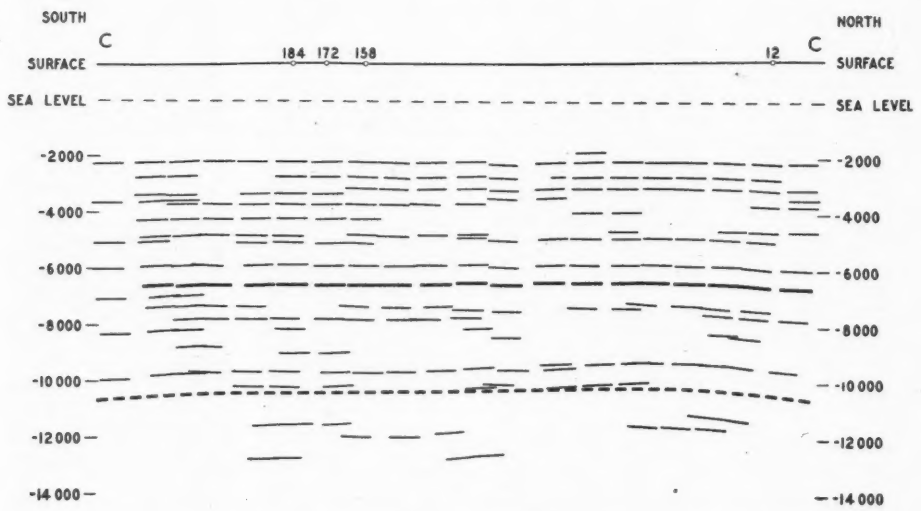

FIG. 14. Cross section CC′, Ft. Cobb area, Superior continuous reflection data.

the ostracodal limestone in the upper Hoxbar. Comparison of the geological and geophysical data shows 135 feet of relief on this marker between the two Superior wells, 80 feet on the Amerada Hoxbar map, and 150 feet on the Superior Hoxbar map. It should be noted that the control points on the Amerada map are closer to the Cogdill than the control on the Superior map. The Texas No. 1 Warden is two miles east of the boundary of the Fort Cobb area. On the Hoxbar marker it is 772 feet lower than the Superior No. 1 Weller. The Amerada Hoxbar map shows 500 feet of relief between the Weller and the east boundary of the map. If the geophysical control is extrapolated to the Warden, there would be about 600 feet of relief to compare with 772 feet of relief by geological control.

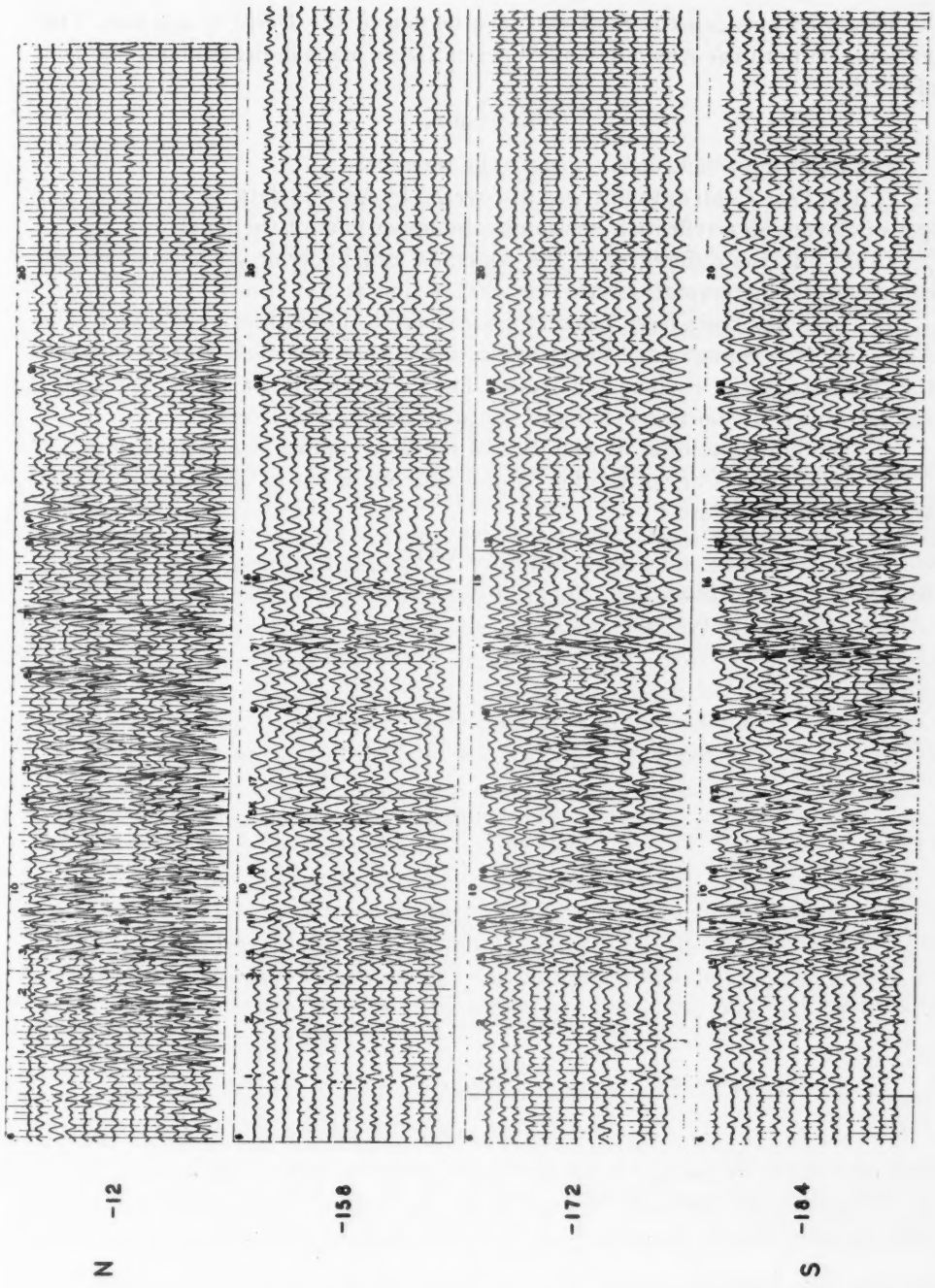

FIG. 15. Superior records for cross section on line CC'.

The relief between the Superior wells on top of the Deese is 219 feet. The contours on both the Amerada and Superior Deese maps indicate about 200 feet of relief.

CONCLUSION

The following conclusions appear to be warranted:

1. The Fort Cobb anticline was discovered by seismic data which shows 200 feet of closure on a reflection horizon in the upper part of the Hoxbar.

2. Despite the differences in the Amerada and Superior seismic techniques the structural interpretations are remarkably similar.

3. Three dry holes have tested the structure to a depth of 17,800 feet. The Amerada No. 1 Sprague and Superior No. 1 Weller were drilled near the crest of the structure in the Hoxbar and Deese. The Superior No. 1 Cogdill was drilled 200 feet down the northeast flank of the structure on the Deese.

4. The limited amount of well control tends to confirm the seismic data.

5. So far the history of the Fort Cobb anticline is one of geophysical success and commercial failure.

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THE CASE FOR GRAVITY DATA FROM BOREHOLES*

NEAL J. SMITH†

ABSTRACT

The immediate urge for gravity meter surveys in boreholes is the desire to improve the gravity method itself but there are other potential uses for data so obtained. Borehole gravity surveys, through the influence of density, would be related to numerous important rock properties such as the velocity of seismic waves, the coefficient of reflection, the electrical resistivity, lithology, porosity, and the kinds and states of fluids in the rock. Therefore, in addition to improvement in gravity prospecting, the data would bear upon seismic techniques and, depending on accuracy and detail, upon the interpretation of lithologic and electric logs. The more obvious of the possible uses are indicated and some of the problems and inherent limitations holding up development are discussed.

INTRODUCTION

Solutions to several of the problems preventing gravity meter surveys in boreholes have been found or are in process. Instrument size, temperature control, and operating range are three major ones and, to a degree, remote control reading and leveling are others. Advances in these last were achieved primarily through experience in underwater gravity operations in the Gulf of Mexico. But the problems remaining are formidable. It is the purpose of this paper to indicate uses for gravity data from boreholes in the hope that a display of the possibilities will increase interest in the subject and contribute pressure for the improvements which must still be made before such data can become available.

There are three distinct fields in which gravity borehole data are potentially valuable;

(1) in the interpretation of surface gravity surveys,

(2) in the interpretation of seismograph data,

(3) in the interpretation of the borehole geology.

The first of these has received the bulk of attention to date, partially because the natural sponsors of the method are interested in gravity and partially because from the standpoint of instruments and accessory equipment it is closest to realization. The second and third, however, are intriguing and may eventually prove the more important.

BOREHOLE GRAVITY IN THE INTERPRETATION OF SURFACE GRAVITY DATA

Borehole Gravity Components and Their Separation

In general the meter in the borehole will be subjected to three influences which are functions of depth. The first is the free air effect accounting for the decrease in gravity with increase in elevation. The second is the Bouguer effect

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which accounts for the attraction due to materials whose densities are laterally constant, or to a reasonable approximation, to the layered section where dips are flat to gentle. The third may be called the anomalous influence. It accounts for the gravitational disturbances caused by mass distributions in the earth which do not conform to the Bouguer conditions of horizontal density layering.

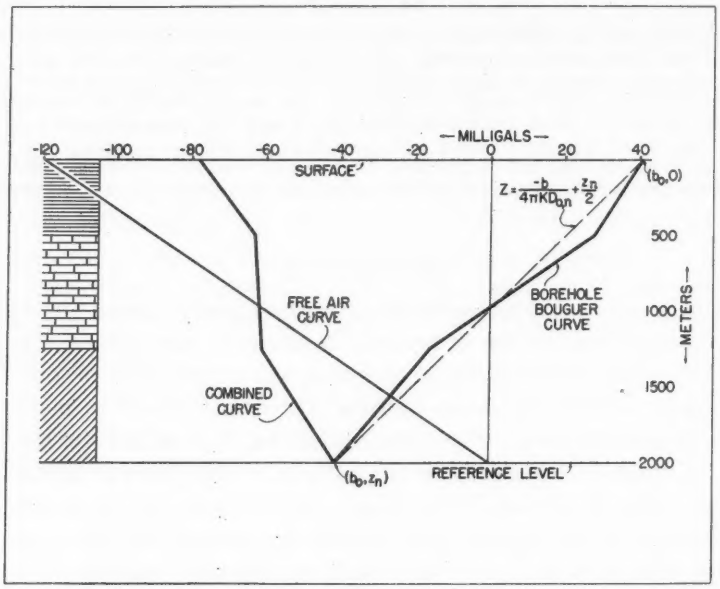

FIG. 1. Free air and borehole Bouguer influences separately and combined. The Bouguer curve represents the resultant attraction of material between reading point and the surface and between reading point and reference level as would occur along a borehole. Average slope of the curve is inversely proportional to average section density.

The free air effect is effectively linear with depth over the distances with which we can expect to operate (0.9406×10^{-4} gal per foot, or 0.3086×10^{-3} gal per meter). Its chief bearing on the problem is that being opposite in tendency to the Bouguer influence it very materially reduces the total range of gravity difference which the borehole meter must compass. The Bouguer attraction for a surface position assuming that the materials beneath are horizontally stratified as to density and effectively infinite in horizontal extent, can be stated as,

$$b_o = 2\pi K[d_1h_1 + d_2h_2 + d_3h_3 + \cdots + d_nh_n] \tag{1}$$

where K is the gravitation constant (6.67×10^{-8} in *CGS* system), d is density and h the thickness of the individual beds. The subscripts refer to the layers in sequence from the surface down.

Now it is obvious that a gravity meter read in a borehole would be positively influenced by that part of the section below it but negatively by that above, thus, for a position in a vertical borehole at the bottom of layer 2,

$$b_2 = 2\pi K[d_3h_3 + d_4h_4 + \cdots + d_nh_n - d_1h_1 - d_2h_2] \tag{2}$$

or, at the bottom of any layer i,

$$b_i = 2\pi K[d_{i+1}h_{i+1} + d_{i+2}h_{i+2} + d_{i+3}h_{i+3} + \cdots + d_nh_n - d_1h_1 - d_2h_2 - d_3h_3 - \cdots - d_ih_i]. \tag{3}$$

For present purposes the Bouguer influence is of interest only to the depths reached by the gravity meter; i.e., the subscript n in the formula represents either the lowermost layer surveyed by the meter (Fig. 2), or one farther up the hole when shallower emphasis is desired but always of course the lowest member in

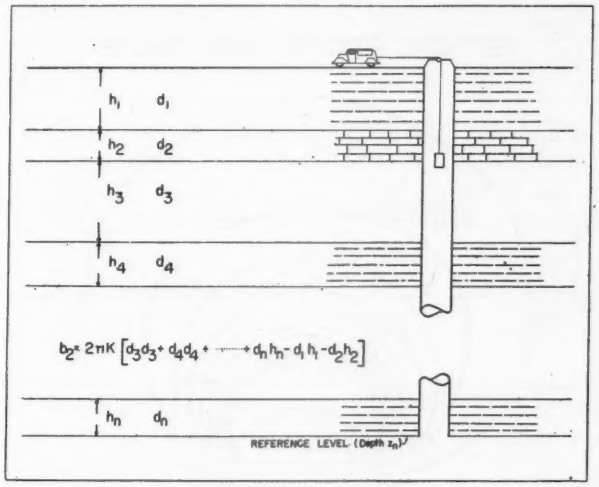

FIG. 2. The Bouguer conditions—plane layering laterally homogeneous. The Bouguer attraction at the base of the second layer.

the series. The mathematical presentation can be condensed by letting z equal depth, positive direction down, so that z_i is the sum of layering from the surface through h_i, and z_n is the sum from surface to the maximum depth under consideration. Also let D equal average density over the vertical interval indicated by the subscripts.

$$b_o = 2\pi KD_{o,n}(z_n) \tag{4a}$$

$$b_i = 2\pi K[D_{i+1,n}(z_n - z_i) - D_{o,i}(z_i)] \tag{4b}$$

$$b_n = -2\pi KD_{o,n}(z_n) \tag{4c}$$

Note that b_o equals minus b_n. That is, the downward attraction at the surface due to the selected part of the penetrated section is equal to the upward pull of that same section at the reference depth z_n.

As mentioned previously, in addition to the Bouguer influence described, the meter will be affected by the free air component and by anomalous density dis-

tributions either above or below z_n. Latitude influence can be neglected if the hole is vertical. Thus the meter will record:

(5a) $G_o = b_o - Cz_n + g_o$ at the surface,

(5b) $G_i = b_i - C(z_n - z_i) + g_i$ at depth z_i,

(5c) $G_n = -b_o + g_n$ at depth z_n.

Where C is the Free Air constant, z_n is depth to reference level, and g is a function representing influence due to mass distributions that do not conform to

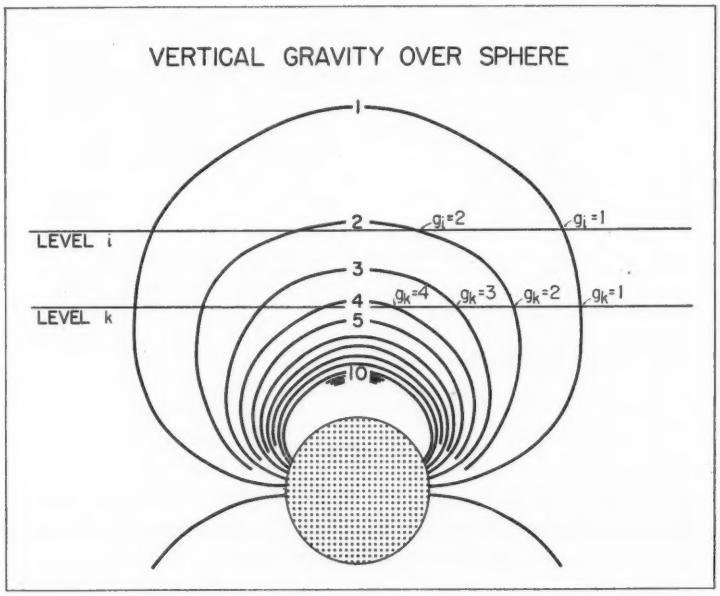

FIG. 3. Vertical component of gravity configuration over spherical mass. Shows intersection of iso-anomaly surfaces with vertical section. Indicates (a), anomaly function g increasing rapidly with depth over central area and (b), decreasing with distance out from center on levels i and k.

the Bouguer concept of parallel, essentially horizontal, layering, i.e., g is the anomalous function.

Subtracting the reading at depth z_n from that at the surface gives:

(6a) $$G_o - G_n = 2b_o - Cz_n + g_o - g_n$$

or re-arranging,

(6b) $$b_o = G_0 - G_n + Cz_n - g_o + g_n/2.$$

The third term in the numerator can be readily evaluated since C is a known constant and z_n would be known by direct cable measurements in the hole.

Figure 3 shows the dependence of the vertical component of gravity due to

an anomalous mass on both lateral and vertical position. It is, of course, the vertical component that the gravity meter measures. The figure shows that the difference between any two levels, $g_k - g_i$ in the diagram or $g_n - g_o$ in the equation, approaches zero rapidly with distance out from center and also with increasing vertical distance of the two levels above the mass. Or, more clearly perhaps in the latter case, $g_k - g_i$ will be small as the corresponding interval $z_k - z_i$ is small with respect to mean depth to the anomalous mass. What has been said here of this anomaly will apply qualitatively to most anomalies related to non-spherical density distributions.

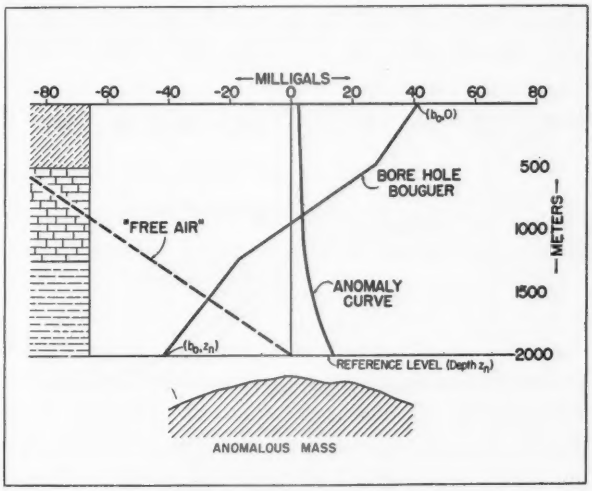

FIG. 4. Free Air, Bouguer, and anomalous mass curves separately.

In the average situation therefore $g_n - g_o$ will be insignificant. Where it is not, that is, where the hole surveyed is well centered over and has a total depth of the same order of magnitude as the depth to the disturbing mass, the function g can be obtained by a mathematical analysis of the surface gravity pattern about the borehole assisted by the gravity data from the borehole (Evjen, 1936; Henderson & Zietz, 1949; Elkins, 1950). Hammer (1938, 1950), some years ago and again recently, has discussed the influence of this anomalous function in terms of the apparent deviations it can produce in measured values of the normal (Free Air) gradient of gravity and makes quite apparent the need for its extraction or evaluation.

It is also possible to approach separation by empirical means. From equations (4) and (6) it is apparent that average density across an interval is a linear function of depth. The slope segments of the Bouguer curve in Figure 4 and the combined Free Air-Bouguer curve in Figure 5 reflect density differences between the adjacent layers. Note particularly the straight, crossed lines in Figure 5. These represent the Free Air-Bouguer curve which would be obtained through

sections of constant density. The line with the lesser slope corresponds to an assumed density of 2.0 gr/cm³ and that with the greater with a density of 3.0 gr/cm³. If these densities are taken as the lower and upper extremes likely to be encountered in the section then the slopes of the corresponding line are the limiting slope values for any part of a Free Air-Bouguer curve through the actual section. Therefore, if the curve obtained by the meter in the borehole had segments whose slopes were less than that of the more gently sloping straight line or greater than the steeper, the deficiency or excess could be attributed to the influence of an anomalous mass nearby.

Specific information in regard to the lithology of the section penetrated would

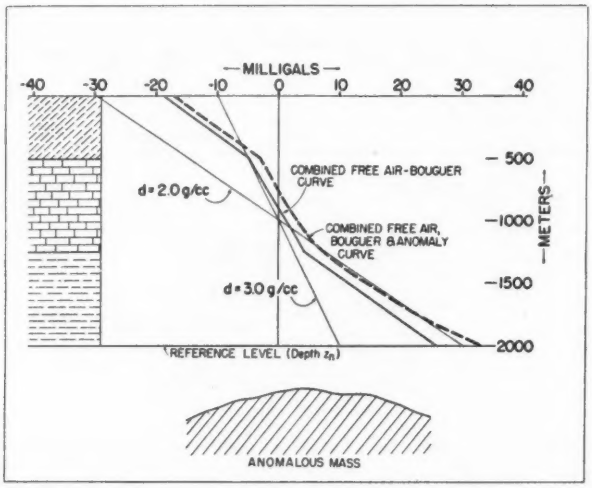

FIG. 5. Free Air, Bouguer, and anomalous mass curves combined. The gravity scale has been doubled with respect to previous figures and zero gravity reference shifted left. Also shows Free Air-Bouguer curves for average formation densities of 2.0 g/cm³ and 3.0 gr/cm³.

serve to increase the resolving power. A bare knowledge of rock type without information on porosity etc. would very often serve to bring the limiting slope lines closer together simply by indicating the presence of absence of rocks capable of either or both density extremes. For instance, if it were known that no significant amounts of anhydrite or dolomite were present, the maximum slope line could be reduced in slope by approximately one-fourth the angle between lines representing densities 2.0 and 3.0 gr/cm³, i.e., the maximum slope would be that compatible with a density of approximately 2.75 gr/cm³. It would be better if densities were measured directly from cores or cuttings from reasonably thick, homogeneous sections, preferably near the bottom of the hole or closest the anomalous mass. Then the exact Free Air-Bouguer slope across such intervals could be calculated for comparison with the corresponding parts of the curve obtained by the gravity meter in the hole. This would permit a relatively exact de-

termination of the anomalous effect at the particular level or levels. Qualitative and sometimes quantitative help would generally be available from resistivity logs opposite deeper shale sections provided the layers were thick enough for accurate density determination by the gravity meter and depending upon how well known the relationships between compaction, resistivity, depth etc. were for the region (Claudet, 1949).

In addition to the above which depends upon borehole data alone, an inspection of the surface gravity map in the vicinity of the borehole would permit an estimation of g_o, the magnitude of the anomaly at the surface, and would also show in the normal case which way the curve would trend with depth. However, see Figure 7 for an exception. It appears, then, that the borehole gravity components could be separated and that the resolving power would be dependent upon the amount and quality of other kinds of data available from the borehole, as well as upon the availability of an adequate surface gravity survey of the area.

Estimating Depth and Shape of the Anomalous Mass

The attraction between two particles is directly proportional to the product of their masses and, inversely, to the square of the distance between them, i.e.,

$$g = (Km_1m_2)/r^2. \tag{7}$$

Any actual anomalous mass has size and shape in addition to distance and the integration of these into the equation generally has the effect of complicating it tremendously. A spherical anomaly, provided the density distribution is symmetrical, offers an exception because its mass may be assumed concentrated at its center so that in effect it can be considered a particle. Thus,

$$g = KM/r^2 \tag{8}$$

where K is the gravitation constant, M the mass of the sphere and r the distance from point of observation to center of sphere. Therefore, in a borehole survey centered over a homogeneous geologic feature of spherical shape the following would hold:

$$g_o = KM/r^2 \quad \text{at the surface,} \tag{9a}$$

$$g_i = KM/(r - z_i)^2 \quad \text{at depth } z_i \tag{9b}$$

etc.

Any two sets of such equations can be solved for M and r. It must be remembered, of course, that r is not the distance to the upper surface of the body but to its center. Even so the information can be valuable because geological limits to density would bracket the sphere's radius. The accuracy of the results in any case depend upon the degree of density homogeneity in the surrounding rock, and the conformity of the shape and density distribution in the body to the spherical.

Geologic features of interest to the petroleum geologist will rarely be associ-

ated with spherical density anomalies. However, gravity-depth curves can be computed for more plausible shapes and density distributions. If these could be compared with the plot of the gravity-depth function g obtained from a borehole survey over a particular anomaly, the relative fit would furnish a valuable clue toward an understanding of the depth, shape, and size of the actual disturbances. Simply as a suggestion of the diagnostic manner in which gravity can vary above and through masses of different dimensions Figure 6 is presented. The curves represent the relative gravity influence along the axes of a set of right circular cylinders each cylinder differing in dimensions but having a common mass. The ratio of radius to length for each of the three from short to long is 4, 1/2 and 1/16. The curves include the case in which the borehole penetrates the anomalous body, a situation comparable to drilling into an igneous plug, or, if signs are reversed, a salt dome.

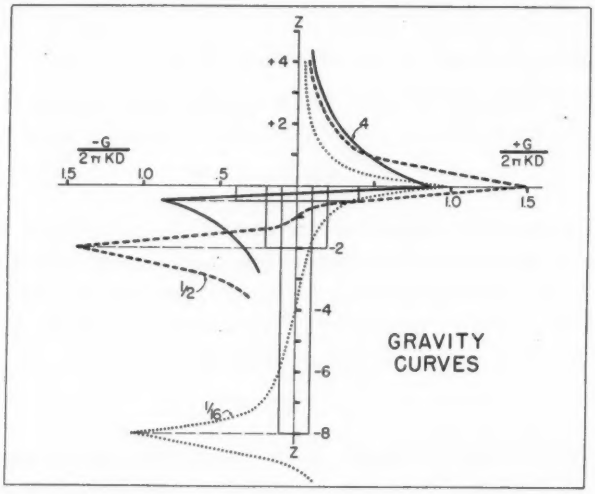

FIG. 6. Gravity versus depth along axes of cylinders identical in mass but of different dimensions. From short cylinder to long the ratios of radius to length are 4, 1/2, and 1/16. Density is unity. Gravitation constant K is dependent on unit of linear measure. Curves are symmetrical about the centers of their respective cylinders.

Figure 7 is added to call attention to the gravity behavior above and through what can be considered an idealized salt dome-cap rock problem, i.e., a short cylinder of positive density contrast has been superimposed on a long cylinder having a negative contrast with the surrounding medium and the gravity effects for axial positions are shown. Allowing for the over-simplification it is still apparent that a gravity meter survey in a borehole penetrating a salt dome could yield valuable information in regard to cap distribution and the shape and extent of the lower part of the salt mass.

Vertical Gradient of Gravity vs. Depth.—The vertical gradient of gravity over a disturbing mass is more sensitive than gravity itself to factors of depth and

shape. The vertical gradient could be obtained directly from a borehole gravity survey with an accuracy dependent upon the success in separating the Bouguer influence of a section penetrated from the depth function g from gravity surveys in boreholes. Thus, from equations 5 and 6 the total vertical gradient is given by,

$$(10) \qquad (G_i - G_k)/(z_i - z_k) = -4\pi KD_{i,k} + (g_i - g_k)/(z_i - z_k) + C.$$

Where G_i and G_k are the readings in the hole across the interval z_i to z_k, $D_{i,k}$ is the average density across the interval, and C is the free air constant. The vertical gradient due to the anomalous mass alone is given by

$$(11) \qquad (g_i - g_k)/(z_i - z_k) = (G_i - G_k)/(z_i - z_k) + 4\pi KD_{i,k} - C.$$

As for gravity, gradient-depth curves can be pre-calculated for bodies of

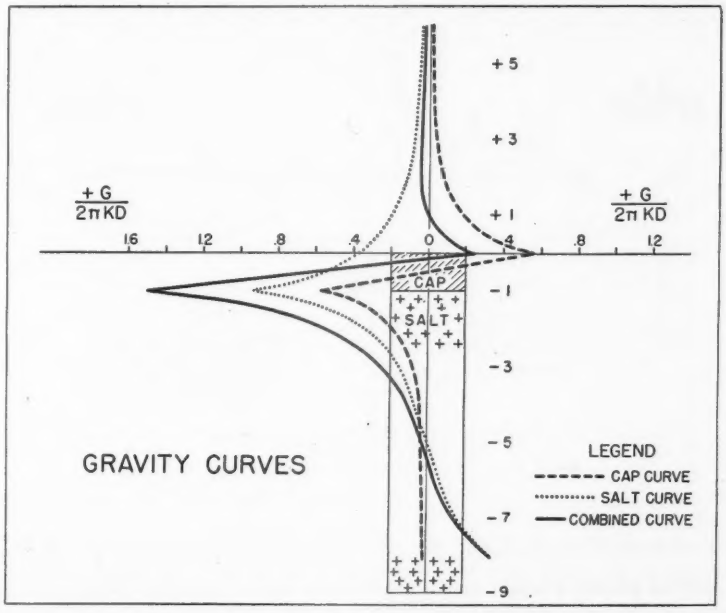

FIG. 7. Gravity versus depth along axes of superimposed cylinders; upper has positive density contrast unity; lower, negative contrast unity—a simplified cap rock—salt dome problem. Gravitation constant, K, dependent on unit of linear measure.

various sizes, shapes and densities for comparison with curves obtained in the actual case. The behavior of vertical gradient symmetrically above and within cylinders of equal mass and volume but having radius to length ratios of 4, 1/2 and 1/16 is shown in Figure 8. Note the sensitive response to shape and distance as compared with the gravity curves (Fig. 6) for the same cylinders. The measurement of the vertical gradient of an anomalous mass should be one of the most interesting fruits of gravity meter surveys in boreholes provided the problems of separation from the Bouguer gradients are not too great.

Supplement to Surface Gravity Data.—It is obvious that borehole gravity and borehole gradient would when used in conjunction with surface gravity permit more definite quantitative studies than could be made on the basis of the surface data alone. This would hold whether one were attempting to calculate the gravity field as it might exist across some other level (Evjen, 1936; Henderson & Zietz, 1949; Elkins, 1950), or were concerned with a single anomaly within which the borehole survey was reasonably well centered.

Direct Uses for Bouguer Function

The Bouguer attraction measured in a borehole could be used to make a reliable point calculation of the so-called elevation correction factor required for

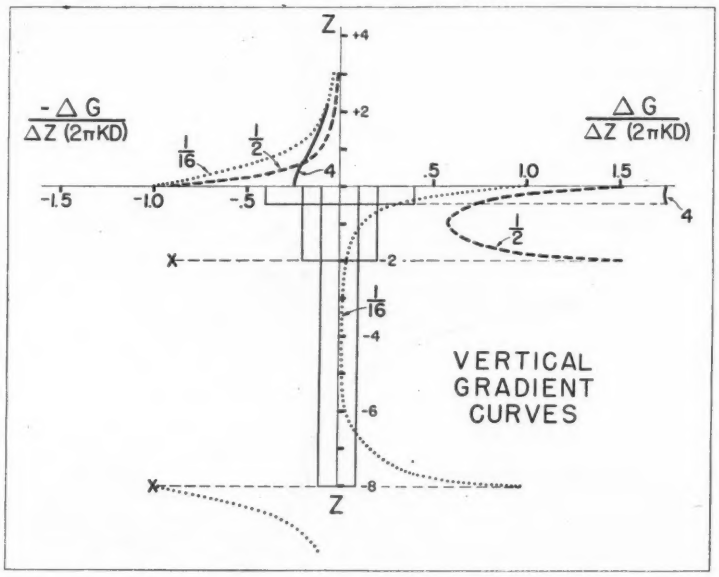

FIG. 8. Vertical gravity gradient versus depth along axes of cylinders identical in mass but of different dimensions. Short cylinder to long the ratios of radius to length are 4, 1/2, and 1/16. Density is unity. Gravitation constant, K, dependent on unit of linear measure. Curves extended through each cylinder are mirror images of upper curves about horizontal plane through cylinder centers.

the reduction of raw surface data. The factor, which is a function of near-surface densities, is ordinarily obtained by empirically compensating for the influence of elevation between selected gravity stations in the area (Nettleton, 1939; Siegert, 1942; Legge, 1944). Where there is insufficient surface relief or too much relief, i.e., terrain effects, the result may not be dependable. In the case of low relief at least the borehole derived factor would be of real service and in any case it would offer a valuable check. While this use is not of extreme importance it is worth mentioning because it would require measurements to only very shallow depths

and thus imposes the minimum physical problems. It also suggests a possible secondary use for shot holes.

Of greater basic interest than the above, a comparison of the Bouguer attraction between holes down to common level would permit a stripping away gravity-wise of the influence of material above that level from the surface gravity map. This feature would be of no value if the Bouguer conditions held strictly throughout the region, i.e., if no lateral density changes took place from one location to the next. In this event the amount of the Bouguer influence down to a particular level would, barring differences in elevation, be the same. But while the conditions

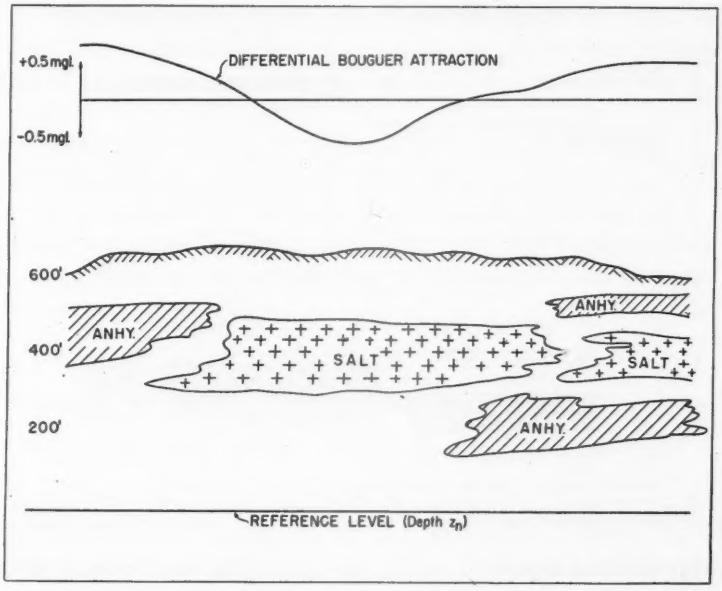

FIG. 9. Distortion left on gravity map due to abrupt, lateral density changes in the upper section. Gravity profile illustrates lateral differential aspects of Bouguer influence above the reference level.

of lateral density homogeneity can be supposed to hold reasonably about a single borehole because the depth of penetration would generally be small compared to the horizontal distances over which appreciable density changes would take place, they can seldom be expected to maintain between well sites.

Suppose continuous lateral density changes are present in the upper section. As a result tilting or warping would be present on the conventional gravity map commensurate with the magnitude and direction of the density changes themselves forming part of the obscuring "regional" background with which the interpreter must contend. This portion of the "regional" would be extracted by application of the differences in the values for Bouguer attraction above a common level as obtained from borehole gravity surveys.

Continuing the theme there are cases not too rare in which abrupt lateral density discontinuities unrelated to favorable structure occur in the upper section. Zones containing lensing evaporites would be one example. Such discontinuities could leave patterns of sufficient sharpness and boldness on the gravity map to mislead the interpreter into belief that here were anomalies of possible economic significance. A net of gravity surveys in boreholes penetrating the critical section might solve his dilemma.

Where a portion of an interesting type of geologic structure extended above the effective level to which gravity surveys had been made, a comparison of the borehole Bouguer effects in the area might help establish that fact. It could also

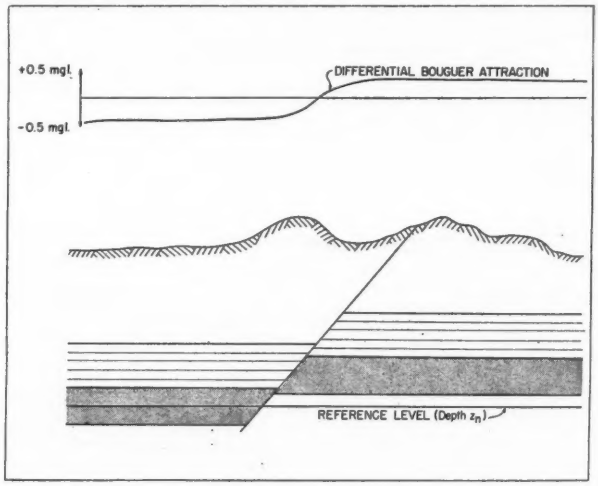

FIG. 10. Gravity profile due to fault in upper section, i.e., above reference level.

permit an approximate separation of the portion of the total anomaly arising from above from that arising from below the reference level.

The accuracy of the method in terms of the resolving power of gravity effects across the boundary would, assuming no inaccuracies in the borehole surveys, depend upon the number of borehole surveys per unit area, their depths, their grouping and upon the geology of the region. For the purpose considered it would be preferable if the boreholes were not located over local anomalies. For the purposes described in the previous section the position over the anomaly would be an advantage. Thus a loss in one direction may be a gain in another.

The Depth-Density Function

One of the several unknowns in every quantitative gravity problem is the density function. Both the density distribution within the anomalous geologic feature and the contrasting density distribution in the country rock are involved. The interpreter must often rely on his concept of the geology to set limits on these. Or, he may be able to approach distribution of density in the country rock

somewhat more directly through use of depth-density curves such as those computed by Athy (1930), Barton (1933), Nettleton (1934) and Hedberg (1936). Other possibilities include a study of lithologic logs from nearby wells, or from actual density measurements on cores and cuttings from these wells. Such data are helpful but have points of weakness. The depth-density curves based on compaction are limited to sections predominantly shale and are, even then, generalizations. The lithologic log as an indicator of density is at best qualitative, and logs compiled from densities measured directly from cuttings and cores must be regarded skeptically from the standpoint of the degree with which the samples can be said to be representative of the section. Further, the experimental work described by Hammer (1950) throws doubt on the degree to which laboratory measured densities of samples taken at depth can be said to be a reliable index of the densities of those same samples *in situ*. This is true especially if the shale content is high.

The gravity borehole survey would provide a means of measuring densities *in situ* over the section penetrated and with a degree of accuracy commensurate with the problem as stated by Hammer (1950). From equations, (5a, b, c) giving the reading values at points along the hole in terms of the Bouguer, Free Air, and function g, it is apparent that the difference in readings at different points in the hole can be represented as follows:

$$G_i - G_k = b_i - b_k - C(z_k - z_i) + g_i - g_k. \tag{12}$$

But substituting for b from equation (4a, b, c), and re-arranging gives

$$D_{i,k} = [G_i - G_k + C(z_k - z_i) - g_i + g_k]/4\pi K(z_k - z_i) \tag{13}$$

which could also have been obtained from equation (11). Now $g_k - g_i$ must either be so small that it can be neglected for the immediate purpose, or where not effectively zero could be evaluated as indicated earlier. Therefore, the density can be determined.

Since points i and k are any reading points, the interval $z_k - z_i$ can be made as small or large as desired and can be positioned anywhere along the hole. Hence, the density across any interval can be obtained provided gravity readings have been taken across the interval. A series of readings along the hole would provide data for a complete density curve, one which would give the measured values of rock densities as they exist at depth. No other method appears capable of providing equally reliable data on bulk densities of the formations in place. A possible exception might come through development of the quantitative relationships between formation resistivities, depth age and density as implied by Claudet (1949). But this last would be restricted to shales and even then would require a considerable amount of subsidiary information for local calibration.

Accuracy

Most gravity meters used in surface work are reliable to the nearest 0.1 milli-

gal. For the uses so far proposed accuracy to the nearest 0.2 milligal would suffice. It is not necessary to consider at this point the influence of the hole as a function of diameter, deviation from gage, casing, collars, or cement. This is taken up quantitatively in the next section. Surveys need not be confined to open holes thus adding an increment of operational safety to the process and suggesting that, when the technique has been developed, old wells in the workover stage in addition to those currently drilling can be utilized to build up a mass of data

BOREHOLE GRAVITY IN THE INTERPRETATION OF SEISMIC DATA

Coefficient of Reflection

The ability of an interface at depth to reflect sound waves is a function of density, velocity, wave length and angle of incidence. For sharp density and velocity discontinuities and layers thicker than one wave length, wave length can be ignored (Wolf, 1937), and for most reflection work the energy can be considered vertically incident. Under these conditions the reflection coefficient can be expressed in terms of density and velocity alone. (Rayleigh)

$$R = (d_2V_2 - d_1V_1)/(d_2V_2 + d_1V_1) \tag{14}$$

where d is density and V longitudinal velocity. Subscript 1 refers to the medium in which incident and reflected waves travel, subscript 2 to the medium acting as reflector. The coefficient, which is always less than unity, is the ratio of amplitude of reflected to incident wave, and its sign indicates whether the reflection will be returned in, or 180° out of phase whith respect to the incident wave. Thus, when R is positive, i.e. $d_2V_2 > d_1V_1$, a compression is reflected as a compression, but when R is negative, a compression is reflected as a rarefaction.

Identifying Reflecting Horizons.—From the nature of the reflection coefficient it is apparent that it can be used to suggest where in the section reflections might arise. It has been customary, due to a general lack of density data, to assume densities constant in making such calculations (Beers, 1940), but West (1941), using densities measured from well cuttings has shown how drastically coefficients calculated on the basis of velocity variation alone can differ from these obtained by use of both measured densities and velocities. If densities from borehole gravity surveys were available from holes surveyed for velocity, material would be at hand for calculating more dependable coefficients as a routine matter. Comparison of coefficients so obtained with those based on velocity alone, or with ideas based on lithology, would probably explain the frequent absence of reflections from horizons where they had been anticipated as well as their appearance where they had not. Furthermore, given density and velocity surveys of sufficient detail and accuracy, the resulting reflection coefficient—depth function would make it possible to estimate in advance the relative amplitudes between reflections expected from definite zones. This could be done with sufficient reliability that the amplitude patterns could be used, locally at least, in identifying the reflections with the related subsurface characteristics within those zones. To

make use of such an advantage would, of course, require attention to some of the prevalent systems of automatic volume control and to other distorting characteristics of instrumentation.

As far as density is concerned, sufficient accuracy and detail for this speculated use would be obtained from gravity borehole surveys in which readings were made at intervals along the hole on the order of 100 feet and with an accuracy of ± 0.2 milligal. To match this, velocity surveys would require an increase in detail of some three to four times over that currently customary and, in addition, a like increase in accuracy. Many will agree that, quite aside from the present discussion, an improvement of this nature is overdue for borehole velocity surveying.

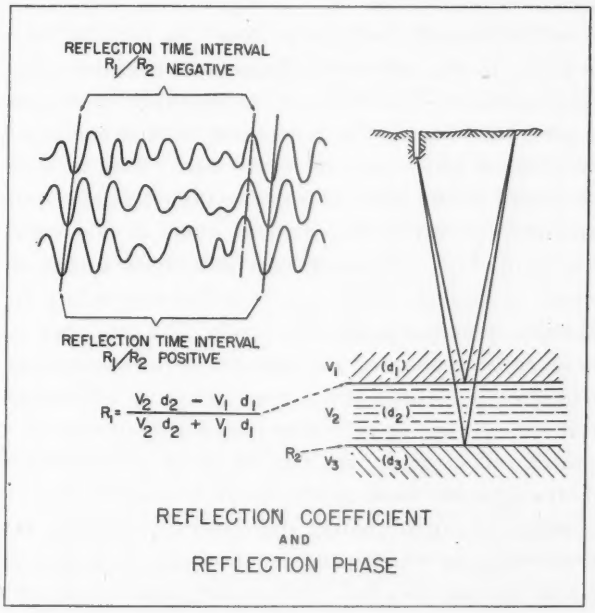

FIG. 11. Influence of the relative sign of the reflection coefficient on the apparent time interval between reflections. Reflections related to coefficients having like signs are timed between like apparent cycles of the respective wave trains—the current custom. Reflections related to coefficients having opposite signs should be timed between opposite phases of the forward parts of the respective wave trains.

Arrival Phase in Reflection Timing

The relative phase with which reflections arrive at the surface, i.e., is whether the initial movement imparted to the ground surface is the same or opposite in direction, is a function of the sign of the coefficients of reflection at the responsible interfaces. If the coefficient is positive an incident compression pulse is reflected as a compression and vice-versa for a rarefaction, i.e., the reflected wave is in phase with the incident energy. If the coefficient is negative an incident compres-

sion pulse is reflected as a rarefaction and a rarefaction as a compression, i.e., the reflected and incident waves are 180 degrees out of phase. Obviously, for a given burst of incident energy, reflections from interfaces having coefficients of opposite sign will be out of phase by 180 degrees and will force opposite motions of the ground surface relative to their initial arrivals. Other things equal, the reported electrical analogues will also be 180 degrees out of phase.

This matter is ignored in routine practice, i.e., all reflections are assumed to arrive in like phase as regards the influence of the reflection coefficients as though all coefficients were either positive or negative. While the general increase of both velocity and density with depth certifies that the majority of coefficients will be positive our knowledge of the variation with depth of both velocity and density in particular cases makes it certain that an appreciable number of reflections are related to negative coefficients, perhaps as much as twenty-five per cent of the whole in certain areas. In the nature of things these negative coefficients will not tend to be grouped together. They will tend to be singly interspersed between the more numerous positives, hence, the reflections related to them must be effectively 180 degrees out of phase on the record with those adjacent. If these inverted types are picked in the same manner as their neighbors they will be mistimed by an amount equivalent to one half cycle of the effective frequency dominating the system. This will result in time interval errors of ± 0.01 to 0.02 second or, in terms of footage, from 25 to 150 feet depending on the frequency and the interval velocity at the particular depth. The tendency would be for the larger discrepancies to be associated with greater depths as a result of the combination of lower frequency returns and higher velocities acting there. This could be of considerable importance in problems involving faulting of small throw, in attempting to match reflection depths against those of subsurface markers, and in pinchout and stratigraphic work generally. In this last connection it should be noted that the coefficient could change sign laterally, passing through a no reflection stage in so doing, in which case the standard technique in timing would result in what would amount to a half cycle mis-correlation of the same reflecting horizon.

Obviously, this whole question of phase, together with more involved problems not discussed, must be begged in the absence of adequate density and velocity data. The density data could be supplied by the borehole gravity survey.

The Elastic Constants

Longitudinal wave velocity may be written

$$V = [(\lambda + 2\mu)/d]^{1/2} \tag{15a}$$

or

$$V = [(3k + 4n)/3d]^{1/2} \tag{15b}$$

where λ and μ are Lame's constants, k and n bulk modulus and rigidity, and d is density.

These expressions show that a knowledge of in-place density and of longitudinal velocities would make possible direct calculations of the effective elastic constants at depth. With the addition of transverse wave velocities the scope would increase. This possibility should be of considerable interest to the theoretical seismologist in his attempts at reconciling classical theories of elasticity with actual behavior of the earth under stress. It might also be of practical interest to engineers concerned with structural resistance to natural earthquakes.

BOREHOLE GRAVITY IN THE INTERPRETATION OF BOREHOLE GEOLOGY

Density Logging

Density at any point in a sedimentary column is directly related to mineral composition, porosity, and the kinds and amounts of fluids in the rocks, and, through these, to a number of other qualities such as electrical resistivity, heat capacity and conductivity, induration and compaction. It therefore follows that a knowledge of the manner in which density varies through the column will contribute to a knowledge of all these qualities. It likewise follows that, since density tends to remain constant parallel to sedimentary layering and to undergo maximum change across layer boundaries, a knowledge of density variation with depth will assist in locating these boundaries.

TABLE I

Rock Type	Bulk Density Range	Modifying Factors
Clay Rocks	1.20–2.70	Burial depth, hydration, age.
Diatomaceous shales	0.90–2.50	Fluid content, purity, opalization, etc.
Rock salt	2.10–2.40	Purity, percentage anhydrite.
Gypsum	2.20–2.50	Purity, percentage anhydrite.
Sandstone	2.00–2.60	Porosity, sorting, cementation, fluid types and percentages.
Limestone	2.00–2.75	Porosity, purity, fluid type, percentage magnesium carbonate.
Dolomite	2.10–2.90	Porosity, purity, fluid type, percentage excess calcium.
Anhydrite	2.50–3.00	Percentage impurities especially gypsum or rock salt.

Table I illustrates approximate variations in bulk density within rock types commonly encountered in sedimentary basins. On the basis of the table a density log could give useful information without other assistance where the upper or lower extremes were involved. For example, a measured density below 2.2 gr/cm^3 would limit rock type to shallow clays, to diatomaceous shales, to rock salt, gypsum or to highly porous, gas filled sand or limestone. Geologic expectancy would then generally permit the elimination of several of these possibilities. Clays, or ordinary shales, for instance, could not maintain so low a value at depths much beyond 2,000 feet. Diatomaceous shales have a restricted distribution, and the occurrence of either halite or gypsum in sufficient bulk and purity indicates unusual and specialized conditions of deposition. Similarly, measured densities above 2.7 gr/cm^3 would suggest, even in the absence of other information, dense limestone, or dolomite or anhydrite.

Given assistance from other kinds of logging, lithologic, core and electric in particular, the useful range of the density log would increase considerably:

Lithologic Log.—A lithologic log would relieve the density log of the need for considering the lithologic element and would permit the latter to point to significant changes in porosity and, sometimes, fluid content. This could be especially interesting in limestone sections where the method might distinguish porous zones not apparent from either cuttings or the electric log.

Core Log.—In conjunction with core logging the density log would make analyses of types and states of fluids in the formation more positive and complete. This follows because from the core, laboratory measurements of porosity and grain density would be available for comparison against bulk density in which the influence of the fluids in place is effective.

Electric Log.—In conjunction with resistivity data, by virtue of the relation between porosity, resistivity and density, porosity estimates and ratios of fluid types could be determined with more certainty and directness than is now generally possible. Consider the simple case in which a relative increase in resistivity opposite a sand might be due either to shaling up, or to local increase in cementation, or to the presence of oil or gas. In the first instances, density would increase; in the last, it would decrease. Hence between the two kinds of data an otherwise ambiguous situation might be clarified.

Layer Thickness.—Across a sequence of layers of different lithologies the density log could often indicate both the position and thickness of each layer. Failure would occur when the various factors bearing on in-place density combine differently in adjacent beds to produce like densities.

Correlation.—Strata should tend to maintain their relative density differences laterally with as much faithfulness as they do most other measurable properties. To the extent that this holds density logs should assist in correlation from borehole to borehole.

Form of Density Log.—As illustrations of the forms in which density logs might be presented, note Figures 12a and 12b, both graphing the changes of density with depth for a simple hypothetical section.

Slope Type Density Log.—Figure 12a shows density differences as variations in slope out from the vertical, vertical being taken as the direction for average density. Thus the tangent of the angle between a line segment and the vertical is a measure of the magnitude of the density difference from the average. The sign of the angle indicates the direction of density difference, the positive sense being taken clockwise from the vertical, the negative counter-clockwise. As a convention for plotting it has been assumed that a difference in density of 0.1 gr/cm^3 will be equivalent to a change in tangent value of ± 0.4. Since the average density in the example has been taken at 2.5 gr/cm^3 a positive difference of 0.25 gr/cm^3 would be indicated by a slope of forty-five degrees down to the left and would indicate the presence of a bed of density 2.75 gr/cm^3. A bed whose density is 2.25 gr/cm^3 would have a slope of forty-five degrees down to the right. Note that the effects of differential densities are cumulative in this type graph, a suc-

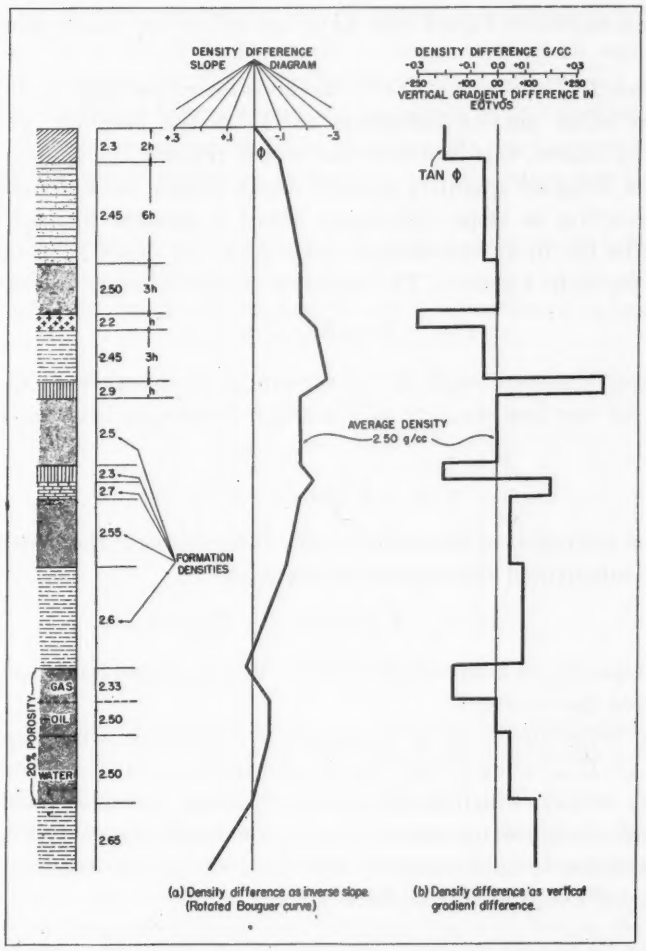

FIG. 12. Equivalent density logs. (a) Gravity or slope type; density versus depth in terms of slope away from vertical. Vertical represents slope of average section density, here assumed 2.5 gr/cm³. (b) Gradient or direct; density versus depth in terms of vertical gradient differences from the mean.

cession of beds below average density swinging the graph wide to the right and vice versa. To estimate density difference of any segment its slope can be matched against the slope diagram at the top of the log.

On this type graph the projection of a slope segment on to the vertical axis gives the thickness and the position of the related layer.

The Gradient Density Log.—Instead of plotting the density variations in terms of slope out from a median vertical reference the value of the tangent of the angle of deviation can be plotted directly as abscissa. This is equivalent to plotting vertical gradient differences from the mean as abscissa at a scale such that a density difference of 0.1 gr/cm³ is equivalent to approximately 84 Eötvös.

Such a graph is shown in Figure 12b. Layering effects are much more obvious on this type.

The Bouguer Difference Function.—Methods for extracting the Bouguer function from the other gravity influences active in the borehole were discussed earlier. It is, of course, this function that would register the density layering. A plot of such a Bouguer quantity against depth would show density variations through the section as slope differences about a straight line whose terminal points would be $(b_o, 0)$ at the surface and $-b_o, z_n)$ at depth z_n in the manner of the Bouguer curve in Figure 1. The equation of this average line is,

$$z = -b/4\pi KD_{o,n} + z_n/2, \tag{16}$$

hence its slope is proportional to the reciprocal of the average density of the section, and for any line segment of the graph proper, as between depth points i and k,

$$z = -b/4\pi KD_{i,k} + Z, \tag{17}$$

where Z is the intercept on the vertical axis. If for density, the density difference $D_{i,k}-D_{o,n}$ is substituted the expression becomes,

$$z = -b/4\pi K(D_{i,k} - D_{o,n}) + Z', \tag{18}$$

which is the equation of a line whose inverse slope is proportional to the variation of density from the average.

If across intervals z_i to z_k segments are plotted with slopes equal to $-1/4\pi K(D_{i,k}-D_{o,n})$ a log of the type shown in Figure 12a will result.

If $4K(D_{i,k}-D_{o,n})$, which is the vertical gradient variation from the average Bouguer gradient, is plotted against depth the graph shown in Figure 12b will result. This reduces to approximately 838 $(D_{i,k}-D_{o,n})$ for densities in grams per cubic centimeter and gradient in Eötvös units.

Limitations of the Gravity Meter

The possibilities of density logging and the advantages of gravity as a means of measurement have been indicated. There are, however, certain inherent limitations in the gravity meter as a logging instrument. The graphs in Figure 12a and Figure 12b are plotted as continuous functions of depth. Instruments capable of producing continuous curves are those which can be operated while in motion as, for example, those used in electric logging. Unhappily none of the commercially successful gravity meters have this ability and it is hardly possible that they will acquire it. It is the gravity meter's function to measure minute differences in acceleration and when it is read motionless these will be gravitational accelerations. Set the instrument in motion, however, and unless the motion be absolutely uniform and non-rotational it will be unable to distinguish between acceleration changes due to gravity and those induced by the motion of the instrument.

Approximating the Continuous Curve.—A continuous curve can be approxi-

mated by a sufficient number of points, therefore to approach a continuous depth-density curve it will be necessary to make a series of separate readings along the hole with the borehole gravity meter. This will require a delicate balance between the degree of approximation permitted by the problem and the time that can be allowed for the survey. A large separation between readings decreases the running time but decreases the fit between the true curve and the approximation and vice versa.

Accuracy Requirements.—Selection of reading interval is also influenced by the sensitivity or accuracy of the meter. It would be useless to adopt an interval such that the density-created gravity change across it is too small to be detectable.

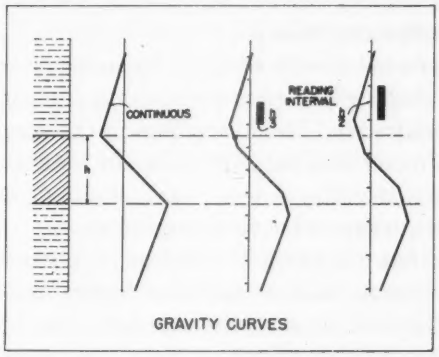

FIG. 13. Reading interval influence on density curve. Shows loss of detail with coarse spacing. Ratio of reading interval to bed thickness should not exceed one-third.

The relation of meter sensitivity to reading interval can be illustrated by example. Suppose six feet is arbitrarily chosen as the minimum layer thickness for which boundary data is to be expected. The reading interval must be several times smaller than the minimum curve segments to be approximated. The ratio probably can not be greater than one-third (see Fig. 13), hence, if the minimum layer is six feet, the reading interval should be no greater than two feet.

The sensitivity requirements of the instrument are dictated both by the reading interval selected and the density difference anticipated across it. For example, the instrument must reliably register to the nearest accleration unit equivalent to:

$$\Delta g' = 4\pi K(\Delta D)(z_i - z_k) = 4\pi K(\Delta D)h/3 \tag{19}$$

where ΔD is the minimum detectable density difference across the chosen interval h. Taking $h/3$ as two feet (ca. 60 centimeters) and selecting 0.05 gr/cm³ as the least density difference to be detected across that interval, $\Delta g'$ becomes as closely as is necessary 2.5×10^{-3} milligals. Equivalent vertical gradient, $\Delta g'/\Delta z$, is approximately 42 $E°$.

Gravity meters in current use in the field can be read by estimation to the nearest 10^{-2} mgl. This is not necessarily a measure of the instrument's accuracy.

It is below that of some and above that of others and is intended to allow accurate reading to the nearest 0.1 mgl. the smallest unit conformable with the accuracy of horizontal and vertical surveying control used in correcting gravity readings. Although there are meters whose inherent sensitivity is greater than 10^{-2} mgl. there has been no need for them to display it because for surface gravity surveying it is an over-refinement.

It appears, therefore, that to meet the arbitrary conditions used in the example above, i.e. ability to discriminate layering on the order of six feet with a density contrast of 0.05 gr/cm^3, the borehole meter would have to have an accuracy about 40 times greater than that acceptable for surface prospecting, or an accuracy some 4 or 5 times better than that of the best surface instruments operating under controlled conditions.

Reading Time Requirements.—In addition to accuracy or sensitivity the time required to make each reading is of great practical importance. A two foot reading interval implies five hundred individual readings in the survey of a thousand feet of hole so that, given a meter of sensitivity sufficient to take advantage of so small an interval, it is obvious that the time for each reading could not exceed a very few seconds if detailed surveys were to be practical.

If it were assumed that five seconds would be required to pull the instrument from one position of rest to another two feet higher and that the instrument could be read in another five seconds, the rate would be approximately an hour and twenty minutes per thousand feet of hole. This is not fast, but not prohibitive. Operating a pair of meters simultaneously in the hole would seem to offer the most promise for a major increase in rate of coverage whatever the time required for a reading.

Whether or not it is even remotely possible to construct an instrument combining such extremes of stability and accuracy for operation in a borehole is beyond the scope of the paper and the author. Obviously, an instrument much less sensitive would not be of value as an indicator of thin layering but it is perhaps far-fetched to aim for this particular advantage in the face of proven methods already available for that job. A borehole meter somewhat more sensitive than those in surface use would still be valuable as an adjunct to other forms of logging for the information it would yield on porosity and, occasionally, fluids within selected zones.

The Gradient Meter

If two gravity meter systems were rigidly fastened one over the other and were so linked that the difference in gravity between systems could be read directly, the result would be one form of a vertical gradient meter. The point for which the gradient would apply would lie midway between the gravity meter systems, and the gradient would be the difference reading divided by the amount of separation between systems. Thus,

$$(20) \qquad (G_i - G_k)/(z_i - z_k) = -4\pi K D_{i,k} + C + (g_i - g_k)/(z_i - z_k)$$

or

$$\Delta G/\Delta z = -4\pi K D_{i,k} + C + \Delta g/\Delta z \tag{21}$$

where $z_i - z_k$ equals the separation between gravity sensitive systems in the meter. Or, where density is in grams per cubic centimeter and gradient in Eötvös units.

$$\Delta G/\Delta z = -838 D_{i,k} + 3086 + \Delta g/\Delta z. \tag{22}$$

The term $\Delta g/\Delta z$ accounts for gradients due to anomalous masses within the penetrated section or below. As previously indicated it will either be insignificant or can be evaluated and separated.

The separation between gravity systems in the gradient meter would have an influence on the sensitivity requirements for those systems and upon the ability of the instrument to locate boundaries. Furthermore, the resolving power in terms of minimum detectable layer thickness would be, as in the case for the gravity meter proper, a function of the reading interval. Giving the component gravity systems of the gradient meter sensitivities to the closest 2.5×10^{-3} milligals, as for the ultra-accurate gravity meter, then for a separation between systems of two feet the gradient meter would show a readable deflection when the average density variation across that separation reached 0.05 gr/cm^3, i.e. a difference of 40 Eötvös. If density differences were no larger than this there would be no point to reading the gradient meter at intervals along the hole less than two feet and, as for the gravity meter, six foot layers would be the thinnest it could dependably locate.

As thus explained the advantage of a vertical gradient meter over a gravity meter would lie in its ability to present data ready for immediate plotting. This alone would hardly be sufficient to warrant development of such an instrument. But the gradient meter does offer the possibility, however remote, that it might be made into a continuous reading logging tool, and, in addition, it would be a valuable instrument for surface prospecting.

Possibility of Reading in Motion.—It was stated that the gravity meter was inherently unsuited for development into an instrument which could be read in motion because of its inability to distinguish between non-gravity and gravity accelerations, but the vertical gradient meter, at least theoretically, would be independent of non-gravity accelerations in the vertical direction. Therefore, it might possibly be developed into an instrument that could be read continuously while being drawn along the hole. The advantages of such an instrument over those which must be read at rest would be:

(1) it could complete a survey in less time,
(2) it would yield a continuous, hence more complete graph,
(3) for a given sensitivity of the component gravity systems separated by the minimum distance compatible with minimum ΔD the moving instrument could detect thinner layering than could the type which must be read at rest.

Gradient Meter for Surface Prospecting.—While it was stated that a gravity meter having the sensitivity demanded for borehole logging would be over-sensitive for surface gravity work the same would not be true of a vertical gradient meter. A gradient meter of the accuracy indicated for borehole surveys would also

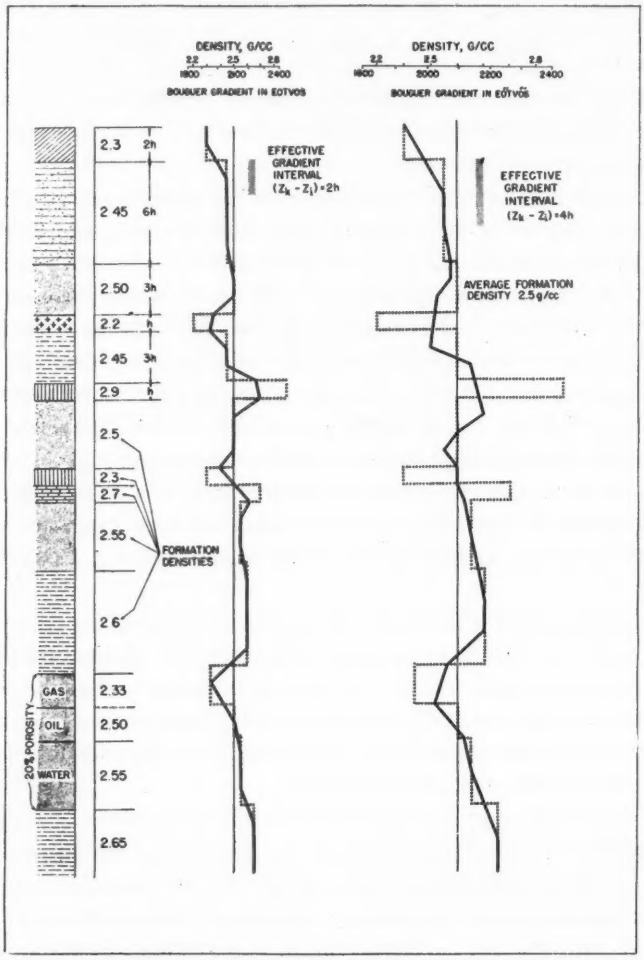

FIG. 14. Density logs via continuous reading gravity gradient meter in borehole. Indicates effects of spacing across which meter measured gravity difference. Short spacing gives sharper definition but less gravity difference and vice versa.

furnish a new and valuable surface prospecting tool which, as compared with the gravity meter, would have

(1) more critical powers of depth resolution,
(2) freedom from the effect of latitude, i.e., horizontal surveying would be needed only for station location,

(3) freedom from the influence of the free air effect, i.e., vertical control would be needed only when surface conditions were unusually irregular in the vicinity of an anomaly.

Compared with the torsion balance it would be considerably less disturbed by shallow density anomalies or topographic features which were horizontally displaced from the station (see Fig. 3).

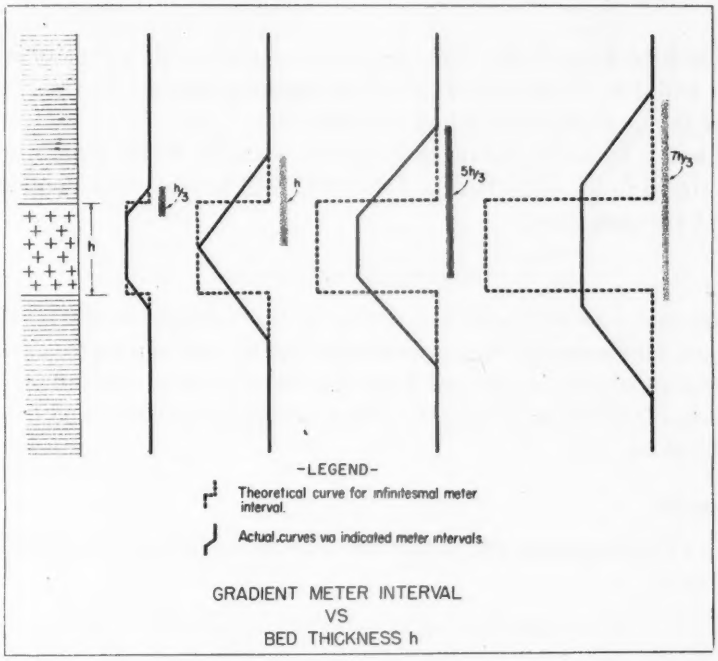

FIG. 15. Continuous vertical gradient curves past isolated bed for different internal system separations.

Spacing Effects in the Gradient Meter.—In Figure 14 the curves which a moving gradient meter would produce across a hypothetical section are shown for two different system separations, one equal to twice the minimum bed thickness h, and one to four times h. It is observable from these curves that the smaller spacing has the greater powers of layer discrimination when adequate density contrast is present, but that the larger spacings are advantageous when layers are thicker and the contrasts in density smaller. Similarly, larger spacings would require less attention to variation in hole diameter as discussed subsequently. In each of these cases the system separation was considered unity so that what is plotted as the abscissa is simply $G_i-G_k-g_i+g_k+C(z_k-z_i)$, where the spacing factor is z_k-z_i. This accounts for the different density scales for each curve, i.e., the density scale factors are proportional to the separation z_k-z_i within the gradient meter. It would seem sensible to run meters of different separations at the same time in

order to obtain the separate advantages of each plus those that would accrue from comparison of the curves as a group, similar to resistivity logging practice. In studying the curves of Figures 14 and 15 as a group tentative rules emerge:

(1) Unless the bed is at least as thick as the separation in the gradient meter the indicated density contrast will be below true value.

(2) Unless the bed is (a) at least as thick as the meter interval or (b) is isolated in a thick, homogeneous section the deflection will not be centered on the bed.

(3) If bed thickness is less than meter separation but if its density is sufficient to register and if it is located in a thick homogeneous section, its thickness will be equivalent to the shoulder width of the deflection.

(4) If bed is equal or greater in thickness than the meter separation the bed will be centered in the deflection and its width will be from mid-shoulder to mid-shoulder of the deflection.

BOREHOLE INFLUENCE

The discussion to this point has neglected the influence ot the borehole upon gravity data. Obviously the hole does disturb the layered symmetry of the density pattern and should be considered from the standpoint of the influence of size, variations in diameter, mud weight, casing, cement placement, and deviations of the hole from vertical.

Hole Diameter

If $b=2\pi Kdh$ expresses the attraction due to an infinite plane layer at any point above it,

$$b' = 2\pi Kd\left[(a^2 + (z + h)^2)^{1/2} - (a^2 + z^2)^{1/2}\right] \tag{23}$$

expresses the attraction at any point on the extension of the axis of a cylindrical hole perpendicularly piercing a plane layer of infinite horizontal extent, where the radius is a, thickness of the plane is h, and distance along the axis from point to the near surface of the layer is z. In another form

$$b' = 2\pi Kdh\left[(A^2 + (Z + 1)^2)^{1/2} - (A^2 + Z^2)^{1/2}\right] \tag{24}$$

where $A=a/h$ and $Z=z/h$.
Then

$$b'/b = (A^2 + (Z + 1)^2)^{1/2} - (A^2 + Z^2)^{1/2} \tag{25}$$

expresses in ratio form the relative gravity influence of the hole in the plane. Table II evaluates the ratio for various combinations of radius and distance and Figure 16 shows the tabular data as a family of curves.

From a table or curves it is apparent that for small values of the ratio a/h the hole effect dies off rapidly with distance because when $b'/b=1$ it has become zero. Also, for small values of a/h the hole influence is slight even at the surface of the plane, i.e. hole entrance.

TABLE 2

b'/b

Z	A				
	1/8	1/6	1/4	1/2	1
0	0.883	0.847	0.781	0.618	0.414
1	0.996	0.993	0.985	0.944	0.822
2	0.999	0.998	0.995	0.980	0.926
3			0.998	0.990	0.961
4				0.996	0.976
5					0.984
10					0.996

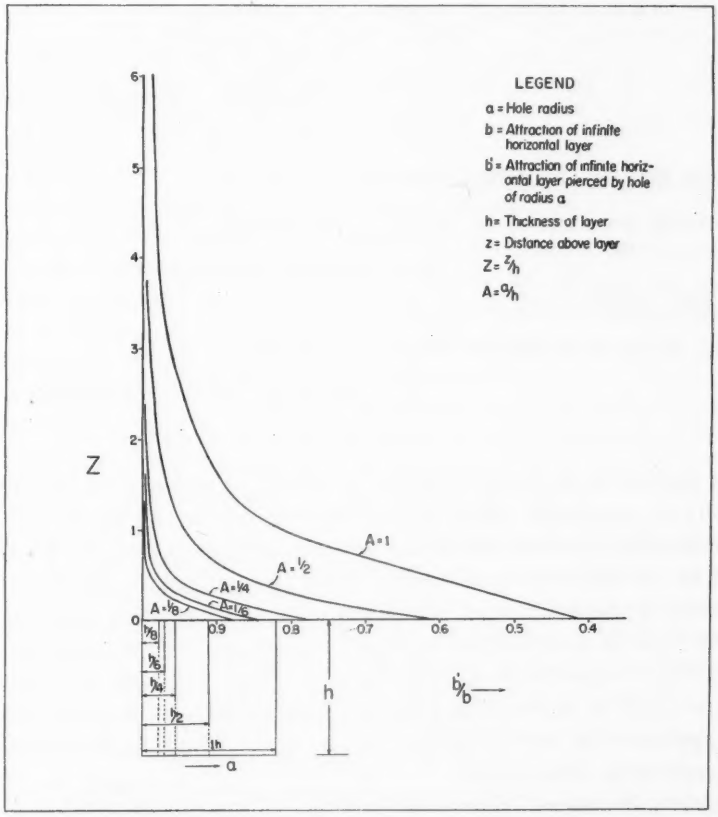

FIG. 16. Influence of hole size on attraction of bed for various ratios of hole radius to bed thickness, a/h, and for various ratios of distance above bed to bed thickness, z/h. Shows effect of hole dies off rapidly with distance for small values of a/h.

If h is taken to be unit or minimum bed thickness and the entire penetrated section is marked off in terms of h so that d_i, d_{i+1}, d_{i+2}, d_{i+3}, d_{i+4}, d_{i+5}, etc. represent average density across successive intervals of thickness h and not necessarily

density across a lithologic layer, then the combined attraction of section and borehole at any point, i, can be written,

$$
\begin{aligned}
b_i' = 2\pi Kh\{ & d_{i+1}[(A^2+1)^{1/2} - A] + d_{i+2}[(A^2+4)^{1/2} - (A^2+1)^{1/2}] \\
& + d_{i+3}[(A^2+9)^{1/2} - (A^2+4)^{1/2}] + \cdots \\
& + d_n[(A^2+(n-i)^2)^{1/2} - (A^2+(n-i-1)^2)^{1/2}] \\
& - d_i[(A^2+1)^{1/2} - A] - d_{i-1}[(A^2+4)^{1/2} - (A^2+1)^{1/2}] \\
& - d_{i-2}[(A^2+9)^{1/2} - (A^2+4)^{1/2}] - \cdots \\
& - d_1[(A^2+i^2)^{1/2} - (A^2+(i-1)^2)^{1/2}]\}.
\end{aligned} \tag{26}
$$

Substituting from Table II in Equation (26) for ratio a/h equal to 1/6,

$$
\begin{aligned}
b_i' = 2\pi Kh[& 0.847d_{i+1} + 0.993d_{i+2} + 0.998d_{i+3} \\
& + d_{i+4} + d_{i+5} + \cdots + d_n \\
& - 0.847d_i - 0.993d_{i-1} - 0.998d_{i-2} \\
& - d_{i-3} - d_{i-4} - \cdots - d_1]
\end{aligned} \tag{27}
$$

hence across an interval from z_i to z_{i+1}

$$
\begin{aligned}
b_i' - b_i'_{+1} = 2\pi Kh[& 2(0.847)d_{i+1} + 0.146(d_{i+2} + d_i) \\
& + 0.005(d_{i+3} + d_{i-1}) + 0.0 + 0.0 + \cdots]
\end{aligned} \tag{28}
$$

similarly for $a/h = 1/4$,

$$
\begin{aligned}
b_i' - b'_{i+1} = 2\pi Kh[& 2(0.781)d_{i+1} + 0.204(d_{i+2} + d_i) \\
& + 0.010(d_{i+3} + d_{i-1}) + 0.005(d_{i+4} + d_{i-2}) \\
& + 0.0 + 0.0 + \cdots].
\end{aligned} \tag{29}
$$

From the above it is apparent that for ratios of 1/6 and 1/4, 85 and 78 per cent respectively of the gravity effect across a layer is due to the density of that layer and that virtually all of the remaining percentage in each case acts on the sum of the densities of the two layers sandwiching the particular one between them. Furthermore, if the average of the densities of the bounding layers is equal to that of the layer in question the reported density will be very close to the exact value. Taking a value for h of three feet, the ratios 1/6, and 1/4 correspond to hole diameters of 12 inches, and 18 inches respectively, both above average size, hence it appears that hole diameter, *per se*, is not likely to be critical for beds thick enough to be detectable.

The above discussion ignores the presence of mud in the hole and of casing. But mud density and casing weight are essentially constant per unit length so that the effect of either or both will be to add a constant increment to the gravity reading except near the ends of the hole, the ends of casing strings, or in the immediate vicinity of collars. The constant disappears in the comparison of readings, and, from the curves in Figure 16, it is seen that the end effects will not be detectable until the instrument is within a distance on the order of three times the hole diameter. When within these critical limits it would not be difficult to com-

pute the effects to be extracted from the log provided mud weight and casing data are available. Similarly, collar influence can be anticipated if sizes and positions are known.

Variations in Hole Size and Other Factors

This problem is fairly complex because of the number of factors entering. Keeping the conventions with regard to constancy of interval h, the attraction at any point i in a borehole of variable diameter can be expressed,

$$
\begin{aligned}
b_i' = 2\pi K h \{ & d_M - D_{o,n} + (d_{i+1} - d_M)\left[(A^2_{i+1} + 1)^{1/2} - A_{i+1}\right] \\
& + (d_{i+2} - d_M)\left[(A^2_{i+2} + 4)^{1/2} - (A^2_{i+2} + 1)^{1/2}\right] + \cdots \\
& + (d_n - d_M)\left[(A_n^2 + (n-i)^2)^{1/2} - (A_n^2 + (n-i-1)^2)^{1/2}\right] \\
& - (d_i - d_M)\left[(A_i^2 + 1)^{1/2} - A_i\right] \\
& - (d_{i-1} - d_M)\left[(A^2_{i-1} + 4)^{1/2} - (A^2_{i-1} + 1)^{1/2}\right] - \cdots \\
& - (d_1 - d_M)\left[(A_1^2 + i^2)^{1/2} - (A_1^2 + (i-1)^2)^{1/2}\right] \}
\end{aligned}
\tag{30}
$$

where the subscripts for A, the ratio of radius to h, indicate that the ratio is not necessarily the same along the hole, and where the factor $(d_{i+k} - d_M)$ represents the difference in density between formation and mud across interval z_i to z_{i+k}. The equation further implies that changes in hole size are abrupt, and extend for distances that are integral multiples of unit bed thickness h. Hence, the hole is pictured as a sequence of drum-shaped cavities along a common axis, each cavity being one, two, three, etc., times h in length.

These conditions permit the maximum possible borehole effect. A cavity not centered on the hole will have less effect than a comparable one centered; a spindle shaped or spherical cavity less than a circumscribed cylindrical one; and a cavity shorter than unit thickness h less than one of length h.

Equation (30) shows that mud weight has a direct bearing on the influence of variations in diameter; the greater the mud weight up to the point at which it equals formation density the less influence deviation from gage has. In fact, if the formation density were constant through the section and if mud weight were brought to equal it there could be no cavity influence at all. Mud weighting is not suggested as a solution but the principle involved does show that cement filled cavities will often give less trouble than those containing mud because the density of cement will generally be closer than that of the mud to formation densities. This suggests that better density logs may be obtained in parts of cased holes than in the same parts of the open hole.

In order to obtain a more distinct idea as to the tolerance to variations in hole size particular solutions have been obtained from Equation (30) for the case in which a six inch hole expands to eight inches and a 12 inch hole to fifteen. For simplification the assumption was made that formation density is constant and equal to 2.5 gr/cm³. Further assumptions are that h, the unit interval, is three feet and that mud density is 1.5 gr/cm³, i.e., 12 lb/gal. The result, shown graphically in Figure 17, is that the three inch expansion of the larger hole introduces a

gravity deflection of the order of 1.5×10^{-3} mgl. within a distance of three feet and that the two inch expansion of the six inch hole introduces one almost as large over a much shorter distance. When the expanded portions contract an oppositely directed deflection is introduced. The example indicates that in the smaller hole larger deviations from gage in terms of percentage can be tolerated. Keeping the other assumptions as stated, substitution of sixteen pound mud instead of twelve would cut the gravity influence of the changes in hole size in half.

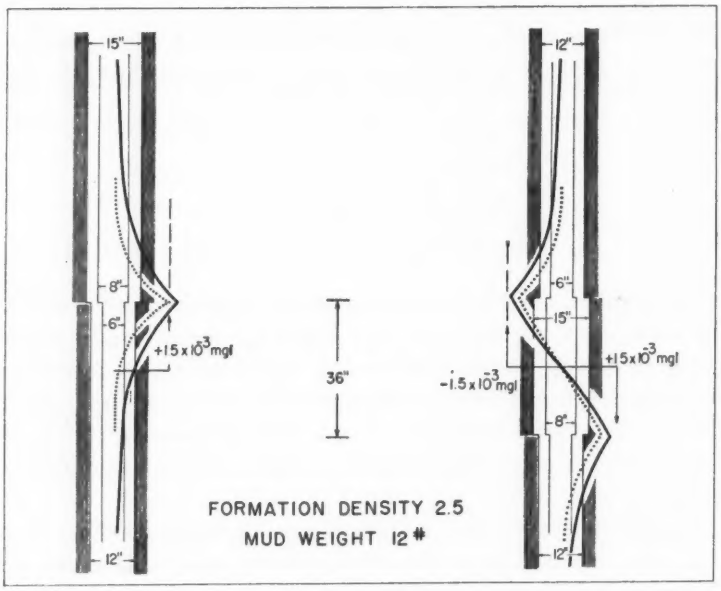

FIG. 17. Gravity influence of variation in hole diameter for single expansion and for expansion-contraction combination. Shows that small holes can tolerate relatively larger variations in diameter, i.e., the six inch hole expanded by one-third gives approximately same effect as twelve inch expanded by one-fourth.

It is apparent that for gravity logs of maximum detail, i.e., six foot layering, a reliable caliper survey of the hole would be needed as a basis for correcting out the hole irregularities. The importance of correction will diminish with the use of heavier muds. The ideal conditions for minimizing both the irregularities and their influence on the meter would obtain where the hole was drilled with heavy muds having low water-loss properties. The importance of variations in hole size also diminishes as the reading interval increases, that is, where a less detailed density log is acceptable. Probably for reading intervals on the order of five feet (minimum layer fifteen feet at ΔD equal 0.05 gr/cm^3) and muds of moderate weight the matter would not be critical.

It is worth noting that where caving is controlled by lithologic boundaries deviations from gage would work to accentuate the boundary indicating feature of the method so long as the less dense material did the caving. This might occur in evaporite sections containing halite or gypsum, in a series of competent lime-

stone beds alternating with friable sands or caving shales, etc. The reverse would hold where the denser medium was eroded.

Non-Vertical Hole and Dipping Layers.—Deviations of the hole from vertical in a section composed of horizontal beds, or a vertical hole in dipping beds, would have similar effects on the density log aside from the influence of latitude. Assuming a small hole and, in the case of dipping beds, large distance from any area of truncation or other abrupt singularity, one effect would be to increase the apparent thickness of layers by an amount dependent upon the angles of deviation or dip as follows,

$$h = h' \cos \theta, \tag{31}$$

where h is the true bed thickness, h' the apparent and θ the angle of deviation or dip.

But this in itself would reduce the apparent density differences between layers by an amount proportional to $\cos \theta$, or,

$$d = d'/\cos \theta \tag{32}$$

where d is the true density difference, and d' the apparent. Of course, if the hole should deviate too greatly from vertical it would be impossible to bring the instrument to level in that part of the hole; hence, reliable readings could not be obtained there.

Hole Drift and Latitude Effect.—To the extent that the hole drifts north or south of the surface position a correction for latitude influence would be required. Directional surveys would be necessary for this purpose.

SUMMARY

Gravity readings in boreholes by instruments of moderate accuracy would be valuable,

(1) in the interpretation of surface gravity surveys generally, and,
(2) in the interpretation of reflection seismograph data when matching velocity information were available, and,
(3) as a means of increasing the effectiveness of other logging methods in regard to interpretations involving lithology, porosity and in-place fluids.

Furthermore, it was shown that greater accuracy would make this third advantage more definite, and that given an increase in accuracy of the order of forty times that acceptable in present day surface instruments without a proportionate increase in reading time a technique of density logging could develop capable of separating quite thin lithologic layers and of furnishing density patterns for use in correlating from hole to hole.

CONCLUSION

In spite of the fact that meters are now available whose size is no impediment and that considerable progress has been made in remote control handling, the problems confronting borehole metering are still formidable even for systems of less than normal sensitivity. However, it is not believed that the solutions are

impossible, and it is suggested that the probabilities for solution will be roughly proportional to the industry's concept of the potential value of the method.

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DENSITY DETERMINATIONS BY UNDERGROUND GRAVITY MEASUREMENTS*

SIGMUND HAMMER†

ABSTRACT

Gravimeter observations, in a vertical shaft, 2,247 feet deep, of the Pittsburgh Plate Glass Company's limestone mine at Barberton, Ohio, for the purpose of determining the densities of the subsurface rock strata, are reported. The survey was made with a standard-type gravimeter to simulate the data which would be obtained by a borehole gravimeter to aid in the anticipation and formulation of problems in the development and application of a borehole gravimeter for gravity prospecting.

Density measurements on many selected core drill rock samples are compared with the densities determined from the gravimeter data. The individual sample measurements show large scatter and systematically low values. Attempts to restore the samples to initial conditions underground were unsuccessful. It appears that density determinations of finite intervals of underground rock strata can be done better with the gravimeter than by laboratory measurements of rock samples.

INTRODUCTION

The fundamental cause of gravity anomalies on the earth's surface and consequently the fundamental basis of all gravity prospecting is the variation of the densities of the rocks in the earth's crust. This has been recognized for a long time, and a great deal of work has been done to determine the densities of various rocks by laboratory measurements of samples, well-cores, and cuttings. The data obtained in this manner are important and useful. This method, however, has severe limitations and serious disadvantages so that nothing approaching a comprehensive program has ever been attempted.‡ To facilitate the measurements, a direct reading attachment on the Jolly Balance has been developed to read the densities directly from the weighings of the samples in air and immersed in a liquid (Bailey, 1945). However, as we shall see from the present data, it does not appear hopeful that we will ever get adequate density data for prospecting needs from sample measurements. Therefore, the determination of subsurface rock densities, in place, is an important practical problem.

Early attempts to determine densities by pendulum measurements of the rate of change of gravity with depth in mine excavations were made by Airy, 1854, and von Sterneck, 1882–85, in Europe¶ and Hayford, 1902, in the North Tamarack Mine in Michigan. Hayford's gravity measurements (Duerksen, 1949) lead to the following very reasonable results, which apparently have never been published:

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† Gulf Research & Development Company, Pittsburgh, Pa.

‡ Personal communication from Thomas B. Nolan, Acting Director, U.S.G.S., 1944.

¶ For a brief critical historical review of this work, see Poynting and Thompson, *A Textbook of Physics—Properties of Matter*, London, 1934, especially pages 35–36.

Depth Interval	Δg	*Density*
0–1,200 feet	+27 mg.	2.81
1,200–4,600 feet	+79 mg.	2.78

The only published report known to the writer on density determinations by underground measurements with a gravimeter is by Heinrich Jung (1939) who made a series of four observations in a nearly vertical line to a depth of 351.4 meters (1,150 feet) in the Wilhelm Mine at Clausthal, Germany, in 1939, with a Thyssen gravimeter. Theoretical aspects of the problem have been considered by H. Lorenz (1938). This work has demonstrated that very useful results can be anticipated from density determinations by underground gravity measurements with modern high precision gravimeters.

This has been realized for a number of years and consideration has been given to the design and construction of a small, remote-control gravimeter for use in boreholes. The construction of such an instrument presents formidable design problems and has not yet been brought to fruition. Diligent consideration of the problem is highly desirable, because density determinations from underground gravity measurements have the advantage that they give the integrated bulk density of the rocks, in place, which is the quantity of fundamental importance in gravity prospecting.

The present investigation was undertaken to simulate the data which would be obtained with a borehole gravimeter to fix ideas on various aspects of the problem and to formulate the procedure for reduction of the data. The results are reported in detail in the rest of this paper.

THE OBSERVATIONS

The gravity observations were made in the limestone mine of the Columbia Chemical Division of the Pittsburgh Plate Glass Company at Barberton, Ohio, with a standard-type small-size Gulf gravimeter. Readings were taken at approximately 200-foot intervals in Shaft No. 2 on the sollars (a horizontal framework of 6-inch steel girders set in concrete in the rock walls of the shaft and covered with a steel grid) from the surface to the floor of the mine at depth 2,246.6 feet. The elevations of the sollars were supplied by Mr. W. R. Flack, Civil Engineer of the mine, and were stated to be accurate to a small fraction of a foot. All readings with the exception of the surface station and the station in the mine at the foot of the shaft were taken in a vertical line. The surface station, which served as the base for the observations, was located 75 feet due west of the entrance to Shaft No. 2. The station on the mine floor was observed 12 feet east of the center of the elevator entrance. The horizontal displacement of these two stations from the vertical line of the other stations is negligible. Shaft No. 2 is for personnel, service, and ventilation, and measures 8×17 feet outside the steel and is lined with concrete (Morrison, 1943; Riddell and Morrison, 1944). An attempt to read the gravimeter in the elevator cage was unsuccessful as adequate steadiness could not be obtained by blocking the cage against the sides of the

shaft with crowbars. Taking the readings on the sollars was somewhat inconvenient due to lack of clear space and a cold draft of the ventilating air, but the quality of the data was good.

Two sets of readings were made with the stations being observed in the same order from top to bottom of the shaft. The gravity results are given in Table 1. Comparison of the two runs shows a maximum difference of 0.21 mg. and an average difference of 0.08 mg. which, as will be seen in what follows, is quite adequate for the present purpose.

TABLE 1

OBSERVED GRAVITY DIFFERENCES IN MINE SHAFT
In Milligals

Station (Depth Below Surface in Feet)	Run 1	Run 2	Average
#1 (Surface)	0	0	0
204	+ 4.92*	+ 4.89	+ 4.90
396	+ 9.65*	+ 9.61	+ 9.63
604	+14.63*	+14.67	+14.65
796	+19.26	+19.13	+19.20
1,004	+24.19	+23.98	+24.09
1,196	+28.57	+28.36	+28.46
1,404	+33.38	+33.38	+33.38
1,596	+37.84	+37.72	+37.78
1,804	+43.12	+43.12	+43.12
1,996	+47.96	+47.79	+47.88
2,202	+52.72	+52.68	+52.70
2,246.6 (Mine Floor)	+54.17	+54.09	+54.13

* Read in mine cage; corrected to elevation of sollar.

As a check for possible anomalous gravity variations in the area which could influence the evaluation of the results, horizontal gravity surveys were made in the mine and over a larger area on the surface of the ground. These will be considered later. The gravity datum for all the observations was determined by gravimeter ties into U. S. Government pendulum stations at Dover, Ohio (Station 395), and Kent, Ohio (Station 457). The two determinations checked within 2 mg. The data on the local base station in front of the entrance to Shaft No. 2 is as follows:

Station	*Latitude*	*Longitude*	*Elevation*	*Adopted Gravity*	*Bouguer Anomaly* $\sigma=2.67$
1	41°00.90′	81°39.03′	1,045 feet	980.1895	−0.0187

REDUCTION OF DATA

The reduction of all data was done by conventional methods, except for the development of special techniques and charts to facilitate the calculation of the corrections for the mine excavations, especially on the stations in the mine shaft and in the mine itself. The terrain corrections for the surface topography on the

underground stations were calculated from extensions of the author's tables (1939). The corrections for the stations in the mine shaft are listed in Table 2.

TABLE 2

TERRAIN CORRECTIONS FOR STATIONS IN MINE SHAFT
In Milligals

Station	Surface Topography $\sigma=2.4$	Shaft $\sigma=2.7$	Mine $\sigma=2.7$	Total
#1 (Surface)	+0.03	0.00	0.00	+0.03
204′	−0.14	0.00	0.00	−0.14
396′	−0.21	0.00	0.00	−0.21
604′	−0.22	0.00	0.00	−0.22
796′	−0.20	0.00	0.00	−0.20
1,004′	−0.16	0.00	+0.01	−0.15
1,196′	−0.12	0.00	+0.01	−0.11
1,404′	−0.07	0.00	+0.01	−0.06
1,596′	−0.02	0.00	+0.01	−0.01
1,804′	+0.03	0.00	+0.01	+0.04
1,996′	+0.07	0.00	+0.02	+0.09
2,202′	+0.11	−0.01	+0.05	+0.15
2,246.6′ (Mine Floor)	+0.12	−0.03	−0.31	−0.22

Applying the corrections in Columns 3 and 4 in this table to the observed gravity values in Table 1 above reduces them, in effect, to values which simulate data observed in a vertical borehole of infinitesimal size.

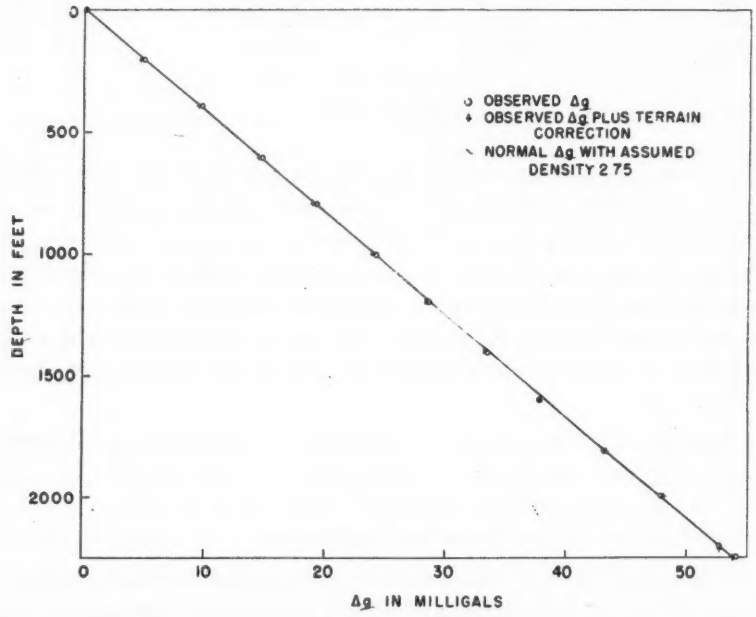

FIG. 1. Observed gravity results in shaft of Pittsburgh Plate Glass Company's Limestone Mine, Barberton, Ohio, October 3, 1945.

The gravity results from Table 1 and as corrected from Table 2 are plotted in Figure 1. For comparison, the straight-line curve showing the "normal" rate of increase of gravity with depth for an assumed density of 2.75 is also drawn on Figure 1. It is apparent from this plot that the gravity data indicate an average density of the rocks penetrated by the mine shaft in the neighborhood of 2.75, but the detailed variations are not well shown on a convenient scale for this figure.

Subtracting the "normal" gravity change, we obtain the vertical "Bouguer" anomaly as shown in Column 6 in Table 3. A plot of these results is shown by the solid curve in the left half of Figure 2. Individual points from the two runs, calculated in this manner, are also shown in Figure 2 to indicate their agreement

TABLE 3

CALCULATION OF DENSITIES OF ROCKS PENETRATED BY MINE SHAFT

Station	Observed Δg mg.	Normal Δg_N* mg.	$\Delta g - \Delta g_N$ mg.	T.C. mg.	Bouguer Anomaly* mg.	ΔB mg.	ΔH feet	$\frac{\Delta B}{\Delta H} \times 10^4$	$\Delta\sigma$† c.g.s.	σ c.g.s.
1										
(Surface)	0	0	0	+0.03	+0.03	−0.15	204	−7.4	+.029	2.779
204	+4.90	+4.88	+0.02	−0.14	−0.12	+0.08	192	+4.2	−.016	2.734
396	+9.63	+9.46	+0.17	−0.21	−0.04					
						+0.03	208	+1.4	−.005	2.745
604	+14.65	+14.44	+0.21	−0.22	−0.01	−0.01	192	−0.5	+.002	2.752
796	+19.20	+19.02	+0.18	−0.20	−0.02	−0.04	208	−1.9	+.007	2.757
1,004	+24.09	+24.00	+0.09	−0.15	−0.06					
						−0.17	192	−8.9	+.035	2.785
1,196	+28.46	+28.58	−0.12	−0.11	−0.23	−0.01	208	−0.5	+.002	2.752
1,404	+33.38	+33.56	−0.18	−0.06	−0.24	−0.13	192	−6.8	+.027	2.777
1,596	+37.78	+38.14	−0.36	−0.01	−0.37					
						+0.41	208	+19.7	−.077	2.673
1,804	+43.12	+43.12	0.00	+0.04	+0.04	+0.23	192	+12.0	−.047	2.703
1,996	+47.88	+47.70	+0.18	+0.09	+0.27	−0.05	206	−2.4	+.009	2.759
2,202	+52.70	+52.63	+0.07	+0.15	+0.22					
						0.00	44.6	0	.000	2.750
2,246.6	+54.13	+53.69	+0.44	−0.22	+0.22					

* For assumed "normal" density 2.75.

† $\Delta\sigma = -39.20\frac{\Delta B}{\Delta H}$ $\sigma = 2.75 + \Delta\sigma$.

in the details of the Bouguer anomaly curve. It is evident that the gravity data show significant local variations in the gravitational gradient. These can only be due to local variations in density of the rock strata penetrated by the mine shaft.

CALCULATING THE DENSITY

The vertical change in gravity in traversing a depth interval ΔH in the underground is given by the well-known relation

$$\Delta g = (F - 4\pi\gamma\sigma)\Delta H + \Delta T \tag{1}$$

where F is the Free Air vertical gradient and $4\pi\gamma\sigma$ is twice the ordinary Bouguer correction constant. This factor has to be doubled because in passing through a layer of rock its downward attraction is removed and its upward attraction is added. The term ΔT represents the variation of the Terrain Correction over the elevation interval ΔH. This term is ordinarily so small that no appreciable error

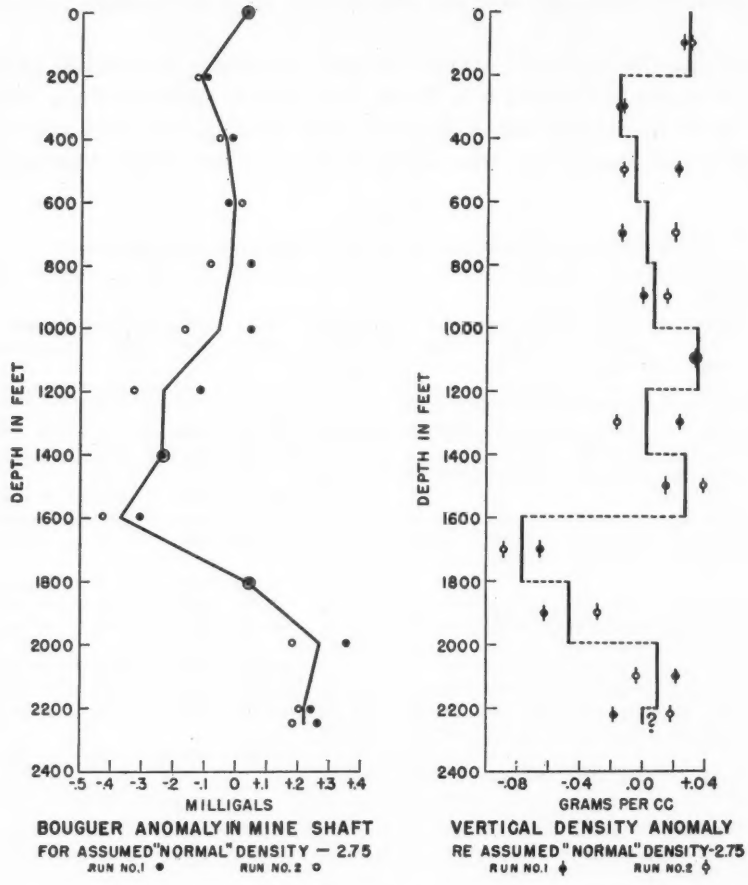

FIG. 2. Anomalous gravity gradient and resultant density variations in mine shaft.

is introduced by using an assumed value of the density for it. Equation (1) may be solved directly for the density giving

$$\sigma = F/4\pi\gamma - (\Delta g - \Delta T)/4\pi\gamma\Delta H. \tag{2}$$

Substituting the "normal" value 0.3086 mg./meter for F and the customary value for the gravitational constant γ, this equation reduces to the practical form

$$\sigma = 3.687 - 39.20(\Delta g - \Delta T)/\Delta H \tag{3}$$

where σ is in c.g.s. units, Δg and ΔT are in milligals, and ΔH is in feet. Note that the gravity value does not change with depth at points where the rock density is 3.687. Ordinarily this condition will not be encountered until depths of many miles below the surface. Equation (3) gives the density directly in terms of the observed gravitational gradient. It is also convenient to calculate the density *variations* from an assumed "normal" value of the density in terms of the vertical "Bouguer" anomaly as defined above. This formula is

$$\Delta\sigma = -\Delta B/4\pi\gamma\Delta H + \Delta F/4\pi\gamma \tag{4}$$

where

$$\Delta\sigma = \sigma - \sigma_0$$
$$\Delta B = \Delta g + \Delta T - \Delta g_N$$
$$\Delta F = F - F_0$$

The subscript $_0$ indicates normal or assumed values. Δg_N is the calculated "normal" gravity change for assumed density σ_0. Again, neglecting possible anomalous influence in the vertical gradient and substituting normal values in the same units as in Equation (3) above, we get

$$\Delta\sigma = -39.20(\Delta B/\Delta H). \tag{5}$$

It may be of interest to point out from this equation that the *slope* and not the magnitude of the vertical Bouguer anomaly curve measures the magnitude of the density anomaly. This means that the required absolute precision of the measured gravity differences must be maintained over the whole range of the measurements. The vertical density anomaly curve shown in the right half of Figure 2 was calculated by Equation (5), as shown in Columns 7–10 in Table 3 above. When desired, the actual density values are obtained simply by adding the assumed normal density used in the calculation of the Bouguer anomaly (in this case 2.75) to the anomalous density values. This result is shown in Column 11 in Table 3.

The subsurface density log determined in this manner shows several significant features and quite definite character. It should be pointed out that the last interval (from 2,202 to 2,247 feet) is uncertain, not only because the interval is small, but also and principally because much of the interval was mined out in the immediate vicinity of the observations. Therefore, the value is strongly dependent upon the calculated corrections and is not of comparable accuracy to the other determinations.

SAMPLE DETERMINATIONS

For comparison with the gravimeter results, density measurements were made on a few hand samples of shales, selected to be representative of the section penetrated by the mine shaft. The measured densities showed surprisingly large discordance with the gravimeter results and it was thought that the samples

selected must not have been representative of the 200-foot intervals tested by the gravimeter. Therefore, arrangements were made to secure a set of samples at 5-foot intervals from a complete set of cores stored at the mine from Core Hole No. 1 which was drilled about two miles southeast of Shaft No. 2 in 1925. Each sample was carefully selected by visual inspection to be as representative as possible of the 5-foot interval. Density measurements on many of these samples, paractically all shales, showed even larger discordance with the gravimeter results

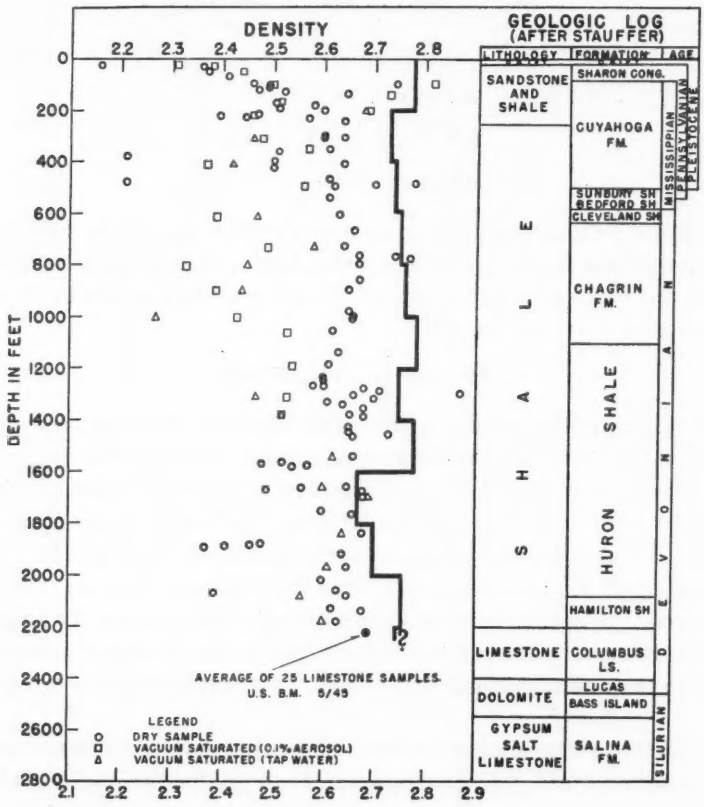

FIG. 3. Density log from gravimeter data and sample measurements.

and a clear systematic tendency toward lower density values. The accuracy of the individual density measurements, as estimated from analysis of the data and checked by repeated measurements, was within 1 per cent and is not an appreciable contributory factor. Soaking and vacuum saturation of the shale samples with water (with and without Aerosol-OT additive to reduce surface tension) made no improvement. The results of all the individual sample measurements and comparison with the gravimeter results and lithologic log after Stauffer (1944) are shown in Figure 3.

It is clear that the sample measurements have so large a scatter that prohibitively many measurements would be required to form a representative average density log over significantly large intervals. It is also evident that the attempts to recover initial conditions by soaking and vacuum saturating (under atmospheric pressure) the shale samples were completely futile. We are convinced that sample measurements on shales of this type are on the one hand prohibitively laborious and on the other hand practically valueless for the purpose of constructing a density log of the actual rocks as they exist underground.

SOURCES OF ERROR

The clear systematic tendency of the density values determined by the underground gravimeter observations to be higher than the sample determinations suggests possible systematic errors in the gravimeter data. A technical evaluation, in general terms, of the sources of error will be given in this section. Specific applications to the present problem will be discussed later.

There are four principal sources of error in density determinations by measurements of the underground vertical rate of change of gravity:

Errors in the gravity readings

These arise from two sources: (a) the precision of the instrument, and (b) the absolute accuracy of the calibration. Source (a) is random in nature; source (b) is systematic.

(a) From Equation (3) above we see that the required instrumental precision depends directly upon the observation interval and, of course, upon the desired precision of the density value. For a desired accuracy of 0.1 c.g.s. units in the density, we have the following relation between precision of the gravity measurement and the corresponding minimum depth interval:

Precision in Δg (mg.)	0.01	0.10	0.25	0.50	1.00
Elevation Interval (feet)	4	40	100	200	400

Thus we see that if the gravity differences are measured to a precision of 0.25 mg. in 100-foot intervals, the densities of 100-foot layers of rock would be determined to 0.1 c.g.s. unit. For other accuracies and intervals, the factors are proportionately larger or smaller as the case may be. For example, a precision in Δg of 0.01 mg. over a 40-foot interval would determine the density to 0.01 c.g.s. unit or over 4-foot intervals to 0.1 c.g.s. unit. It is clear that since the gravity differences involve the differences of two readings, the required instrumental precision conventionally expressed as the probable error of a single observation must be about 40 per cent higher.

(b) Error in the gravimeter calibration causes systematic error in the density values but does not otherwise appreciably affect the character of the density log. The magnitude of the error is dependent upon the density. Solving Equation (1) for the rate of change of the calculated density σ with respect to the rate of change of the gravimeter scale constant (C), we find

$$d\sigma/\sigma = -(F/4\pi\gamma\sigma - 1)dC/C. \tag{6}$$

The scale constant is defined by the relation $\Delta g = C\Delta S$ where ΔS is the gravimeter reading difference in scale divisions. This equation yields the result

σ	1.0	1.5	2.0	2.5	3.0	3.5	3.687	4.0
$d\sigma/\sigma/dC/C$	−2.687	−1.458	−0.844	−0.475	−0.229	−0.053	0	+0.078

For density 3.687, the calculated density is independent of error in calibration because for that particular density the gravity change with depth is zero. As mentioned above, this is mainly of academic interest. For lower densities an erroneously high calibration scale constant yields erroneously low density values and vice versa. However, the magnitude of this factor is not large. For the density range ordinarily encountered in oil prospecting (2.0 to 3.0), a calibration error of 1 per cent introduces an error in the density of only about 0.5 per cent, which is negligible for most applications.

Errors in elevation interval

Since the elevation interval ΔH enters Equation (3) above as the divisor of Δg, it follows that ΔH must be determined to the same relative precision as Δg. As discussed above, this factor varies somewhat with the density of the rocks. However, the required accuracy depends principally upon the desired precision and measuring interval. The approximate relationship is

$$E_H/\Delta H = E_\sigma/(3.687 - \sigma) \tag{7}$$

where E_H is the error in ΔH and E_σ is the resultant error in σ. To determine the density to an accuracy of 0.1 c.g.s. unit over 100-foot intervals, the elevation intervals must be known to an accuracy as given in the following table:

σ c.g.s.	1.0	1.5	2.0	2.5	3.0
E_H feet	4	5	6	8	15

Errors from this source would be random in nature.

Errors in reductions

The principal source of error in the reduction of underground gravity observations, in addition to the factors discussed above, is the correction for terrain effects of the surface topography and for underground excavations in the borehole, mine shaft, or mine. The latter influence is very small, except very near the top and bottom of the excavation, due to cancellation of effects above and below the observation point, as may be seen from the data in Columns 3 and 4 in Table 2 above. In a borehole, variations in size of the hole will be the only factor to consider and will be considerably smaller than in the present experiment. Mud in the hole would greatly reduce the influence of this factor.

Terrain effects of the surface topography may increase considerably with depth. (See Column 2 in Table 2 above.) In hilly country this may be an im-

portant factor. However, the change with depth will always be quite smooth and will not appreciably influence the appearance of local features on the density log.

Anomalous vertical gradient

The value of the Free Air vertical gradient of gravity is a fundamental factor in the determination of the density from the observed rate of change of gravity with depth. Ordinarily the normal value (0.3086 mg./meter) will be used. However, local and regional gravity anomalies will alter the value of the vertical gradient and changes in value of ± 1.5 per cent have been observed (Hammer, 1938). Larger changes on stronger and/or sharper anomalies are possible.

This factor, if appreciable, will cause principally a systematic error in the density determinations, but variable influence is possible if the vertical gradient anomaly is not uniform over the depth interval under consideration. This can only occur if strong and sharp gravity anomalies are present in the immediate vicinity.

The influence of variations in the Free Air vertical gradient on the calculated density value may be deduced from Equation (1). One form of expressing the result is

$$E_\sigma/\sigma = -(F/4\pi\gamma\sigma)(\Delta F/F) \tag{8}$$

where E_σ/σ is the fractional error in density caused by an anomaly ΔF in the vertical gradient value. Substituting the normal value 0.3086 mg./meter for F in the first right-hand factor of this equation, we calculate:

σ	1.0	1.5	2.0	2.5	3.0	3.4	4.0
$E\sigma/\sigma/\Delta F/F$	−3.68	−2.46	−1.84	−1.48	−1.23	−1.05	−0.92

This shows that for a density of 2.0, a 1 per cent anomaly (30 E°) in the vertical gradient causes a change of nearly 2 per cent in the calculated density value. Therefore, this factor cannot be ignored without further investigation.

The magnitude of the vertical gradient anomaly depends upon the magnitude and broadness of the associated gravity anomaly. The vertical gradient anomaly can be calculated by a surface integration of the gravity anomalies shown by a surface survey (Evjen, 1936; Hammer, 1938; Peters, 1949). For the present, let us investigate the vertical gradient due to a spherical mass as this, being the most concentrated mass, gives the greatest vertical gradient for a given magnitude of gravity anomaly. At any point directly above a sphere the following relation holds:

$$G = 2g/Z \tag{9}$$

where G is the vertical gradient anomaly (considered positive downwards), g is the gravity anomaly, and Z is the depth to the center of the sphere. For a sharp anomaly, due to a localized mass anomaly near the underground observation points, a gravity anomaly of moderate size may cause a moderately large and

variable vertical gradient anomaly and resultant error in the density determination as shown in the following table which has been calculated from Equations (8) and (9) for a gravity anomaly of +10 mg.

Z (miles)	1	2	5	10	20	50	100
G ($E°$)	+124	+62	+25	+12	+6	+2	+1
$E\sigma$ (c.g.s.)	−0.148	−0.074	−0.030	−0.015	−0.007	−0.003	−0.001

For other magnitudes of the gravity anomaly the results will vary proportionately. For example, a 100-mg. gravity high due to a concentrated mass anomaly at a depth of 20 miles would cause an anomalous vertical gradient of 62 E° which in turn would erroneously lower the gravitational density determination by 0.07 c.g.s. units. These are the maximum effects. For actual anomalies, which are always caused by finite mass anomalies, the disturbing effect of local or regional gravity anomalies on the density determination will be smaller and usually much smaller. For example, if the gravity anomaly is caused by an extended mass which may be represented by a thin horizontal circular disk, the effect, expressed in the same units as the table above, on the axis as a function of the radius (R) of the disk is as follows:

R/Z	0	1	2	5	10	20
ZG/g	12.43	7.50	4.02	1.46	0.68	0.33

The calculation for $R/Z=0$ (a mass point) checks the result for the sphere considered above, as of course it must. We see from this table that the effect of a gravity anomaly of a given magnitude on the density determination may be as small as 0.1 (for $R/Z=6$), or less, of the effect for a sphere considered above. Therefore, supplementary horizontal gravity surveys to check for errors due to this source need not be made unless the highest precision is desired.

DISCUSSION AND CONCLUSIONS

The principal feature of the present results which requires further discussion is the great discordance between the density values as determined by the gravimeter observations and by measurements of "representative" rock samples. This is best seen on Figure 3. The large scatter of the sample measurements emphasizes the difficulty of attempting to construct a representative density log by this method. The clear systematic tendency of the sample measurements to give lower density values than the gravimeter determinations must now be considered.

As mentioned above in the discussion of sources of error, the principal suspected source of systematic error would be an anomalous value of the Free Air vertical gradient caused by local or regional gravity anomalies in the vicinity of the mine. A regional gravity map based on U. S. Government pendulum stations is shown in Figure 4. A very broad gravity high with about 15-mg. relief is centered near Barberton, Ohio. The vertical gradient anomaly associated with this gravity anomaly is, as can be seen from the type of analysis described above, entirely negligible.

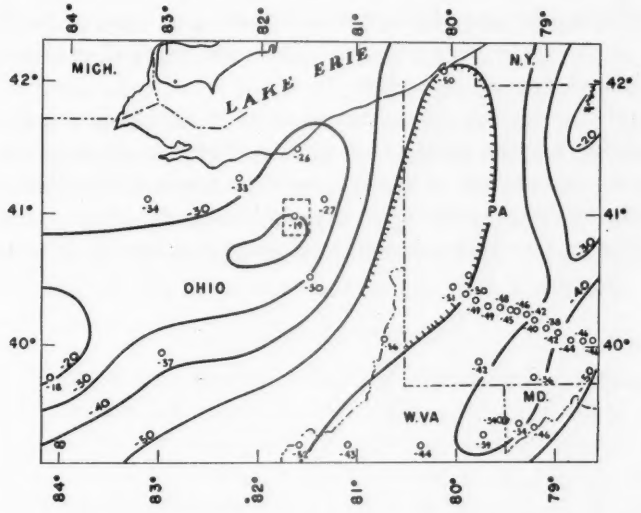

FIG. 4. Regional Bouguer anomaly, mainly from U. S. pendulum data, density = 2.67.

A more local surface survey in the vicinity of the mine was made as part of this investigation to define any local gravity anomaly which, if present, would have a much larger influence on the results. The extent of this survey is indicated

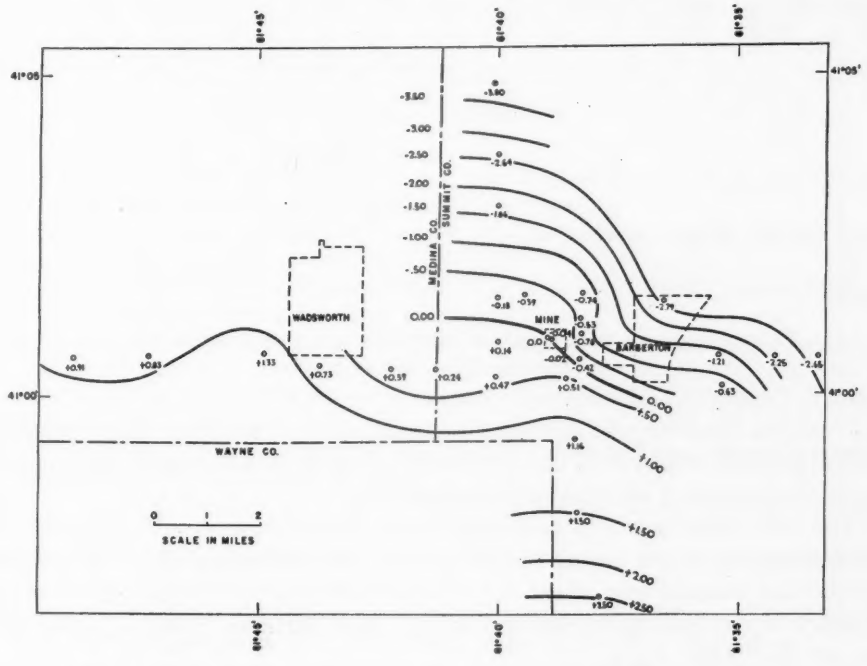

FIG. 5. Local surface gravity survey, Bouguer anomaly with density = 2.775.

by the small rectangle near the center of Figure 4. A map of the results of the local survey is shown in Figure 5. No significant vertical gradient anomaly is indicated in the vicinity of the mine.

As a possibly interesting sidelight, and as a further check, a horizontal survey was also made within the mine. This survey, which is about 2,250 feet underground, extends over an area of about 1,200 by 1,800 feet. The Bouguer Anomaly map, including corrections for mine excavations and surface terrain, is shown in Figure 6. The maximum anomalous horizontal gradient in this survey is about

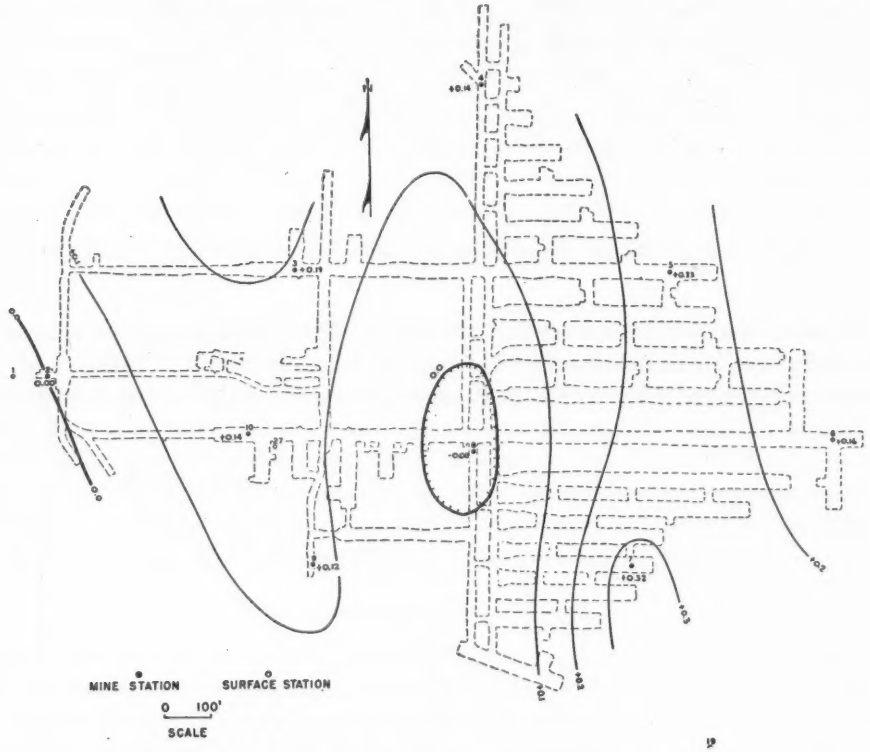

FIG. 6. Bouguer anomaly map from gravimeter survey 2250 feet underground in Limestone Mine, Barberton, Ohio.

26 E° or less than one per cent of the normal vertical gradient. The anomalous vertical gradient would be of the same order of magnitude and is therefore negligible for the purpose of the present investigation.

The only other source of systematic error in the gravity results is the gravimeter calibration. In the present investigation, the calibration of the gravimeter was checked immediately before and after the field trip to the mine. The absolute accuracy of the gravimeter calibration is almost certainly good to better than one per cent (Gay, 1940).

No significant sources of systematic error having been found in the gravimeter results, we conclude that the discrepancy between the density determinations is probably to be attributed to drying or other changes, possibly mechanical associated with core drilling itself, in the samples. Underground rock sampling techniques to eliminate these difficulties have not been developed and may be no less difficult to achieve than the borehole gravimeter. Therefore, we feel that this investigation adds much weight to the growing conviction that density determinations of finite intervals of underground rocks in place can be done better with the gravimeter than by laboratory measurements of rock samples.

ACKNOWLEDGEMENTS

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The gravimeter observations were made by Mr. R. G. Reiser and the writer. The core samples were selected by Mr. L. H. Bailey, who also made the density determinations on the core and hand samples. Most of the figures were traced by Mr. R. D. Craighead. Permission to undertake this research was granted by Dr. Leo J. Peters, Director of the Geophysical Operations Division, and Dr. E. A. Eckhardt, Assistant Director of the Gulf Research & Development Company. The support and interest of all these and others are gratefully acknowledged. The paper is published by permission of Dr. Paul D. Foote, Executive Vice President of the Gulf Research & Development Company.

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DEPENDENCE OF SEISMIC WAVE VELOCITY UPON DEPTH AND LITHOLOGY*

S. S. WEST†

ABSTRACT

Interval velocity v in relatively pure clastic sediments can be expressed as a function of depth z by the formula $v=v_0(1+cz/v_0^4)$, where v_0 is a constant characteristic of the rock and $c=3.3$ km^3/sec^4, approximately. From this relation can be deduced a function $v^4=9.5cz$, which prescribes the minimum velocity possible at a given depth and the maximum depth at which a given velocity can occur. An upper limit of velocity is set by data from limestones and from refraction measurements at depths from 8 to 50 km. The limiting curves converge near 150 km depth toward a function $v^5=180z$, which holds from 200 km to the boundary of the core at 2900 km. The relation of near-surface velocity to porosity is discussed, and it is shown how one can deduce the motion of shorelines during deposition.

A GENERAL VELOCITY FUNCTION

It is frequently stated that age, composition, and depth of burial determine almost entirely the velocity of longitudinal seismic waves in sedimentary rocks, but attempts to isolate these factors and measure the influence of each have not been very successful. Nevertheless, the data published by Weatherby and Faust (1935), by Haskell (1941), and by Navarte (1946) provide an excellent starting point for a general theory.

Haskell (1941) analyzed velocity data from 62 wells in the southern San Joaquin Valley of California, and obtained average velocity-functions for the Pliocene, the Upper Miocene, the Middle-and-Lower Miocene, the Oligocene (Kryenhagen), and the Eocene. A sixth velocity-function was also calculated for an average of all Tertiary formations. As is customary, interval velocity v was expressed in terms of depth z by the relation

$$v = v_o + kz. \tag{1}$$

Haskell's values of the parameters v_o and k are given in Table 1.

It is immediately clear that an inverse relationship exists between v_o and k, and plotting log v_o as a function of log k (Fig. 1) shows that this can be represented within experimental error by

$$k = c/v_o^3 \tag{2}$$

where c is a constant. Data of Weatherby and Faust (1935), Navarte (1946), and Horton (1943) (also listed in Table 1) provide additional points on the graph.

Haskell's data are especially important because the San Joaquin Valley, where they were obtained, is free of large bodies of chemical precipitates, such as limestones, dolomites, salt, and anhydrites. The effect of cementation of grains in clastic material is therefore reduced to a minimum. The Eocene to Recent strata

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TABLE 1

NORMAL INTERVAL VELOCITY FUNCTIONS

Age of rock	Author	Source	v_o	k	kv_o^3
			(km/sec)	(sec^{-1})	(km^3/sec^4)
Pliocene	Haskell	San Joaquin Valley	2.08	0.397	3.57
Upper Miocene	Haskell	San Joaquin Valley	2.41	0.240	3.36
Middle and Lower Miocene	Haskell	San Joaquin Valley	2.17	0.428	4.36
Oligocene	Haskell	San Joaquin Valley	2.65	0.231	4.29
Eocene	Haskell	San Joaquin Valley	1.885	0.581	3.88
avg. Tertiary	Haskell	San Joaquin Valley	2.01	0.464	3.76
Oligocene-Pleistocene	Weatherby and Faust	central U.S.	1.74	0.66	3.47
Devonian	Weatherby and Faust	central U.S.	4.02	0.07	4.53
Eocene	Horton	Vernon Par., Louisiana	1.723	0.8	4.08
Miocene and Pliocene	Navarte	lower Gulf Coast	2.32	0.25	3.13
Eocene (Claiborne)	Navarte	upper Gulf Coast	1.920	0.55	3.88
Eocene (Wilcox and Claiborne)	Navarte	Mississippi	1.770	0.90	4.97
Lower Cretaceous (Trinity), Upper Cretaceous, and Eocene	Navarte	east Texas	1.77	0.7	3.88
					avg. = 3.93

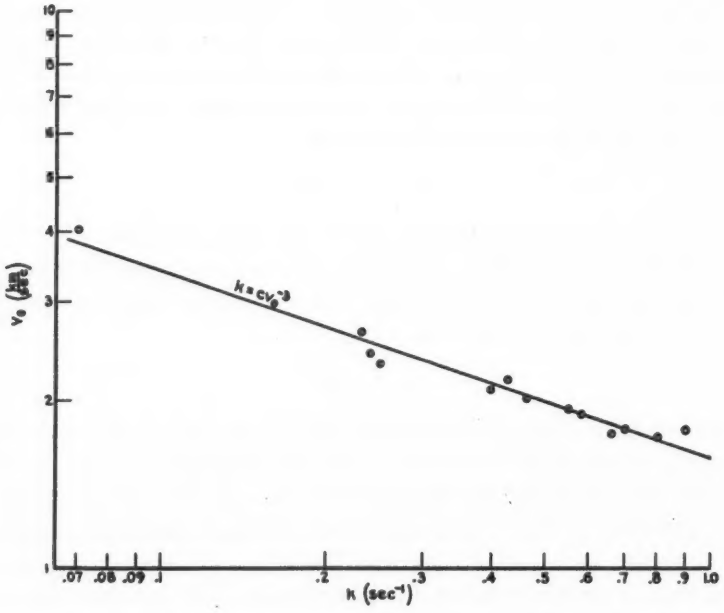

FIG. 1. Logarithm of velocity-intercept v_o as a function of logarithm of slope k for normal velocity-functions of the form $v = v_o + kz$.

are described by Lyons (1940) as evenly bedded limy and carbonaceous shales and arkosic sandstones derived from granodiorites and andesites (probably from Jurassic intrusives, Tertiary rhyolites and Miocene volcanics), quartz being the most abundant mineral and forming up to 75 per cent of the rocks. Hence we can say that relatively pure clastic sediments will have interval velocities given quite closely by the general formula

$$v = v_o(1 + cz/v_o^4). \tag{3}$$

An average of the values of kv_o^3 in the last column of Table 1 gives c the value 3.93 km^3/sec^4, for depth in km. and velocities in km/sec.

Interval velocities of sandstones and shales are thus represented by a function involving only one parameter, v_o. However, the graph of interval velocity as a function of depth usually consists of several such linear segments, rather than a single straight line, because of differences between formations. In addition, the surface velocity will only by chance be the same as v_o, for weathering can make it lower or freezing higher.

UPPER AND LOWER LIMITS OF VELOCITY

If Equation 3 is considered as a function of z and v_o (v being fixed), there will be a value of v_o for which z is a maximum. In other words, there will be a depth below which a given velocity cannot exist, and, conversely, at a given depth there can exist no velocity lower than a certain minimum value. To find the maximum of z, we differentiate Equation 3 with respect to v_o and set $dz/dv_o = 0$, as follows:

$$cz = vv_o^3 - v_o^4 \tag{4}$$

$$c\frac{dz}{dv_o} = 3vv_o^2 - 4v_o^3 = 0 \tag{5}$$

$$v_o = 3v/4. \tag{6}$$

Substituting Equation 6 in Equation 4, we obtain

$$cz = [(\tfrac{3}{4})^3 - (\tfrac{3}{4})^4]v^4 = \frac{27}{256}v^4 \tag{7}$$

or

$$9.5cz = v^4.$$

If the locus is to pass below the lowest velocity function of Table 1, we must have $c = 3.3$ km^3/sec^4, somewhat smaller than the average of kv_o^3. In the (z, v) diagram, no actual velocities can lie on the concave side of this locus, which is (as far as present information goes) the lower limit of velocities in sedimentary rocks.

The highest velocities in shallow formations have been found in limestones.

Weatherby and Faust (1935) found the velocity in the Arbuckle formation (Cambro-Ordovician) to be 5.30 km/sec at the surface and that in the Viola formation (Ordovician) to be 6.10 km/sec at 1.2 km. depth. Navarte's data (1946) include a Permian limestone at 1.44 km. in West Texas, which has a

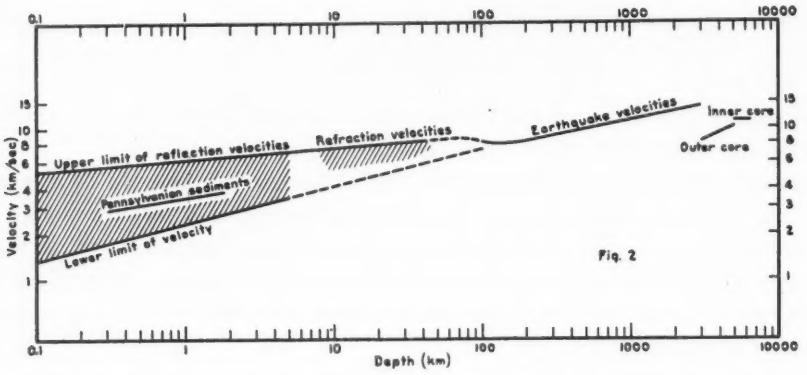

FIG. 2. Logarithm of interval-velocity as a function of logarithm of depth, from the weathered layer to the center of the earth. Shading shows the regions of the diagram in which velocities have actually been observed.

velocity of 5.95 km/sec, and a Devonian limestone at 2.23 km. in the Appalachian Basin, which has a velocity of 6.55 km/sec. These define the upper limit in the velocity diagram of Figure 2, where the lower limit is the curve of Equation 7. The shaded area of Figure 2 is then the region of observed velocities in sedimentary rocks.

VELOCITIES AT GREAT DEPTHS

Birch (1942) and his co-workers have assembled from many sources data on seismic velocities down to a depth of 50 km. These are plotted in Figure 3, together with the above-mentioned velocities in limestones. Velocities obtained by the refraction method or from earthquakes are maxima for the location in question, so these form another portion of the upper limit curve. The recent measurements of Tuve (1948) are also included. The boundary of the group of points in Figure 3 has been transferred to Figure 2 as the upper limit of velocity, and the portion of the graph in which velocities have been observed is marked by diagonal shading. Reflection and refraction measurements are bounded smoothly by the same curve.

Velocities determined by Gutenberg and Richter (1939) and by Jeffreys (1939) have been tabulated by Birch (1942, p. 101), for depths from 100 km to the center of the earth at 6,370 km. At depths greater than 200 km., these velocities lie very close to a function of the form

$$1802 = v^5. \tag{8}$$

A velocity minimum of about 8.0 km/sec exists in the vicinity of 150 km. depth. A major discontinuity (the boundary of the "outer core") occurs at 2,900 km.

THE INFLUENCE OF LITHOLOGY

Available information does not permit any very definite conclusions about the factors which govern v_o of Equation 3. Haskell (1941) observed higher velocities in shales than in sandstones, and it is known that limestones have higher velocities than shales.

Fraser (1935) found that porosity is large when grain-size is small, and that non-uniformity of grain-size increases porosity, which suggests that velocity in-

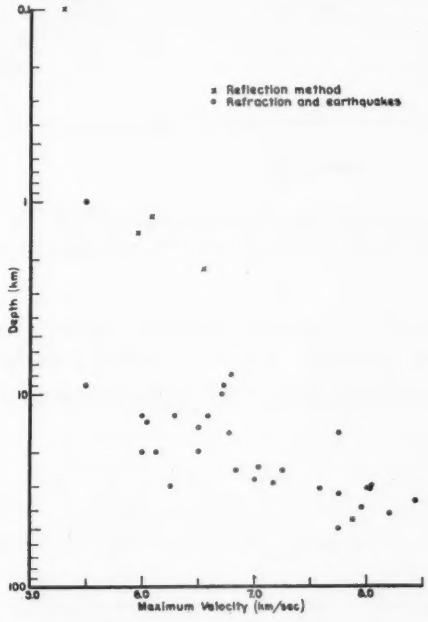

FIG. 3. Logarithm of depth as a function of maximum interval-velocity. Points represent all published data, obtained at many places.

creases with decrease of porosity. We cannot relate the elastic constants directly to porosity, but we can show that density in sediments is almost entirely determined by porosity and that Young's modulus increases generally with increasing density. Data for this purpose are taken from Birch (1942, pp. 20–26 and 73–77), and plotted in Figures 4 and 5. Porosity data are for sedimentary rocks only, but so few values of Young's modulus E were from such samples that all were plotted, those for sedimentary rocks being indicated. Only dynamic measurements of E were used.

Figure 4 shows that the density of porous rocks behaves as though the mean density of the solid crystalline grains were never more than about 4 per cent

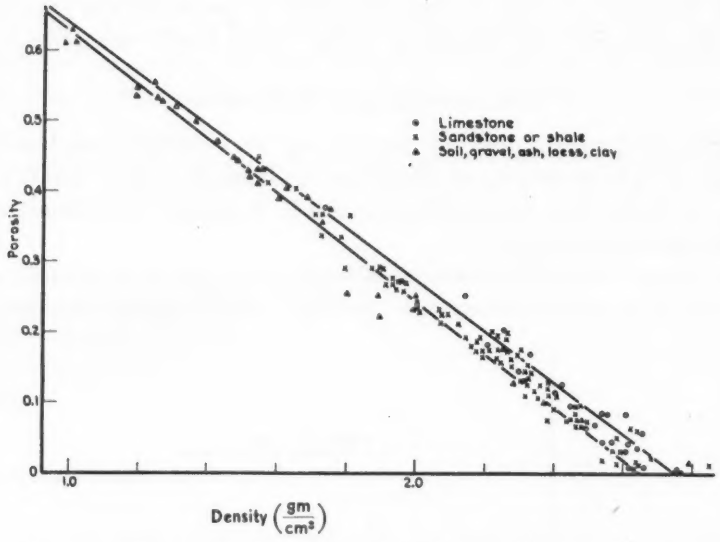

FIG. 4. Porosity as function of density from data tabulated by Birch. The two lines are the functions which would result if the density of all rock were 2.65 or 2.75 gm/cm³, respectively.

different from a value of 2.7 gm/cc³. Hence it appears that density is almost entirely determined by porosity. Figure 5 shows a rapid increase of Young's modulus with density (though with much scatter) quite sufficient to produce the

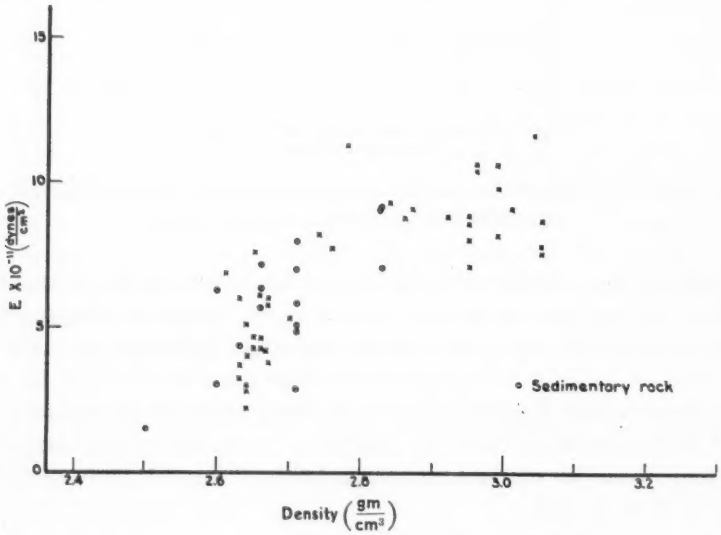

FIG. 5. Young's modulus as a function of density of rock, from data tabulated by Birch.

observed spread of near-surface velocities if it continues at lower densities. It seems very likely, therefore, that the lower limit of velocity corresponds to the maximum porosity permitted by a given overburden, while the upper limit is the velocity attained at zero porosity. Laboratory measurements of the elastic constants of rocks as functions of porosity and composition are needed for a surer statement.

TABLE 2

INFLUENCE OF DEPTH ON VELOCITY IN PENNSYLVANIAN FORMATIONS
(from Weatherby and Faust (1935))

Location	Depth	Interval velocity
Section between Hogshooter and Oswego formations in Oklahoma	0.64 km	3.29 km/sec
	0.67	3.24
	0.88	3.42
	0.98	3.51
	1.07	3.57
	1.10	3.54
	1.25	3.63
	1.28	3.64
	1.59	3.69
	1.74	3.78
Average for Pennsylvanian in central United States	0.31	2.90
	0.76	3.40
	1.07	3.57
	1.37	3.68

A valuable example of the influence of overburden on rock of constant lithologic character is given by Weatherby and Faust (1935), for Pennsylvanian sediments between the Hogshooter and Oswego formations in Oklahoma. These measurements are shown in Table 2, together with the average values for all Pennsylvanian formations measured in the same research, which fit quite well on the curve of the special case. The content of lime in this formation was 14 per cent ± 3 per cent for all wells used, and the mean thickness of the section was 750 feet. In the data of Table 2, depth increases as the seventh power of velocity, so that the slope of the curve when plotted on Figure 2 lies between the slopes of the upper and lower limits. If extrapolated, the curve for Pennsylvanian sediments intersects the lower limit near a depth of 70 km. This suggests that depth (except very near the surface) may be expressed as a constant times a power of velocity for a rock of constant composition and age, the power increasing as the porosity decreases. (An exponential increase of depth with velocity fits the data equally well, but there is no reason for preferring one function over the other.)

GEOLOGICAL INFERENCES FROM INTERVAL VELOCITY

Not all well-logs can be represented by the velocity function of Equation 3. Sometimes a formation is found in which interval velocity increases more rapidly with depth than would be expected from the data of Table 1. Sometimes interval

velocity actually decreases with increasing depth. Nine such cases from the examples of Navarte (1946), are described in Table 3.

In four of these cases the velocities are not far from the lower limit defined by Equation 7. (That two are slightly lower is probably due to error in measuring interval velocity or too short a run of data in Table 1.) We may therefore assume that in these cases the influence of lime or other chemical precipitate is small. If it is a general rule that shales show higher values of v_o than sandstones, it may further be said that the abnormal slope indicates a change of grain-size in the sediments with depth. Thus an unusually large slope would signify that the older

TABLE 3

ABNORMAL VELOCITY FUNCTIONS
(from data of Navarte (1946))

Age of Rock	Location	v_o	k	Minimum interval velocity	
		(km/sec)	(sec^{-1})	*actual*	*permitted*
Devonian (shale)	Appalachian Basin	4.35	0	4.35	2.15
Ordovician to Permian (lime)	west Texas (Permian Basin)	6.90	−0.6	5.10	3.20
Carboniferous	Appalachian Basin	3.80	0.75	4.10	1.75
Permian	west Texas (Permian Basin)	2.75	1.2	4.20	1.95
Upper Cretaceous (Selma chalk)	Mississippi	4.10	−0.4	3.45	2.75
Eocene (Midway shale)	Mississippi	3.00	−0.35	2.45	2.45
Eocene (Wilcox)	upper Gulf Coast	2.07	0.80	2.85	2.35
Oligocene	lower Gulf Coast	0.80	1.0	2.75	2.83
Lower Miocene	lower Gulf Coast	3.65	−0.65	2.45	2.75

part of a formation was shale and the younger part mainly sandy. Conversely, a negative slope would signify even more certainly that older beds were sandy and the younger shale.

This phenomenon is interesting from the point of view of historical geology, for it tells the direction of movement of the shoreline during the deposition of a formation. A negative value of k in Equation 1 thus indicates a shoreline moving inland, with consequent decrease of grain-size of sediments deposited at the place in question. Nevertheless, one must be wary of the influence of a varying content of lime. Let us examine some of the cases in Table 3.

(a) *Midway shale* (*Eocene of Mississippi*).—The Eocene sediments of Mississippi have been discussed by Grim (1936). Over almost the whole of the state, there is a thick calcareous bed at the base of the Midway series, which would cause the velocity function to have a larger slope than normal. In a small part of the area examined by Grim (in west central Mississippi), the Midway is composed of clay with the exception of some limy beds at the top, which could yield a negative slope, showing a reversal of the usual lithologic sequence.

However, Navarte's well-log apparently comes from the extreme southern

part of the state, which is not discussed by Grim, for the base of the Tertiary is at 4,300 feet and the top of the Wilcox (middle Eocene) at 1,500 feet. Of this region Malkin and Echols (1948) state that the shoreline moved inland (transgression) during the deposition of the marine Midway clays, which is the condition for a negative slope.

(b) *Wilcox formation* (*Eocene of upper Gulf Coast*).—The velocity function has an abnormally large slope but velocities only a little above the permitted minimum, the same condition being found in Navarte's log from Mississippi. The section runs from middle to top of the Wilcox. Grim (1936) has concluded that during Wilcox time there was a northward migration of marine waters, followed by a retreat southward. Murray (1947) says that deltaic sedimentation increased during Wilcox time and gradually slackened during the following Claiborne time. Such conditions could produce the observed large slope either by a transition from shale to sand toward the younger part of the formation or by a decrease of lime. Because of the low velocity, the former process is more probable.

(c) *Ordovician to Permian* (*Permian Basin of west Texas*).—Here the top formation is known to be lime and is so noted on the well log. The velocity is not only much higher than the lower limit, but even much higher than the curve of Weatherby and Faust for Pennsylvanian sediments, so the effect of lime is obvious. Hence there is no difficulty in interpreting the negative slope.

(d) *Upper Miocene of San Joaquin Valley, Calif.*—(Not listed in Table 3.) Interval velocity logs published by Stulken (1941), for individual wells in the southeastern San Joaquin Valley show a decrease of velocity from the top of the Miocene down to slightly above the top of the Stevens sand (lower part of Upper Miocene), a distance of 1,000 to 2,000 feet. Here there is known to be little lime, which is confirmed by the fact that the velocities lie close to the lower limit. In the middle Pliocene there is another region where the velocity function has a negative slope. Although the geologic history of the San Joaquin Valley is rather confused, these regions of negative slope appear to correspond to periods of deposition when the beds were sinking faster than sediments were being laid down, thus decreasing the grain-size.

Another mathematical result can be derived from Equation 3. For each pair of values of v and z, only two positive values of v_o are possible, so that only two velocity-functions of the form of Equation 3 can pass through a given point in the diagram of Figure 2. This can easily be seen by writing Equation 3 as

$$(v - v_o) = cz/v_o^3 \tag{9}$$

which is considered now as a function of v_o only, with v and z constant. The roots of v_o occur at the intersections of the curves

$$y = (v - v_o) \tag{10}$$

and

$$y = cz/v_o^3 \tag{11}$$

in the (y, v_0) plane. No matter what the exponent of v_0 in Equation 11 (as long as it is positive), there can be only two intersections in the first quadrant and none in the fourth, so the result is not limited by the slope that was assumed in fitting the data of Figure 1.

In the present state of our knowledge, not much is to be gained from speculation on the physical meaning of this trick of mathematics. Nevertheless, one may note that most of the velocity functions approach the lower-limit curve at their upper (near-surface) ends. Those which approach the lower limit at the deeper end of the range of data from which the function was derived are the shales (such as Haskell's Upper Miocene and Oligocene) and the highly consolidated sediments like limestones. These two groups correspond roughly to the two roots of v_0.

Further measurements in the field and laboratory will improve the accuracy of geological inferences from interval velocities, but even the degree of systematization already achieved extends the range of surface geology a good deal. Careful velocity measurements by the X^2, T^2 method can often yield good enough data to outline the stratigraphy of areas where outcrops are few. The value of such information is especially great in the reconnaissance of large undrilled prospects.

ACKNOWLEDGEMENT

I wish to express my appreciation for the assistance of the Geophysical Institute of the University of Alaska in providing facilities for this investigation.

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NOTE ON WELL-SHOOTING DATA AND LINEAR INCREASE OF VELOCITY*

M. M. SLOTNICK,† J. A. BROOKS, JR.,† AND V. L. REDDING†

The problem of converting well-shooting data into parameters necessary for interpretation is an important one. When the data seem to lend themselves to the hypothesis of a linear increase of velocity with depth, i.e., $v=v_o+ah$, the problem is one of determining the constants v_o and a from the data. We propose to show a

TABLE 1

(Horizontal Distance of Well-Head from Shot-Point, 1000 feet)

Depth of Detector Below Shot-Point h	Average of Corrected Travel-Times t
2528	0.398
2928	0.441
3328	0.485
3728	0.528
4128	0.573
4528	0.614
5008	0.665
5098	0.674
5308	0.692
5428	0.705
5531	0.715
5931	0.750
6063	0.762
6198	0.775
6316	0.784
6626	0.813
6797	0.829
6953	0.841
6993	0.845
7236	0.869
7419	0.884

practical and relatively simple method of determining these constants from a typical set of data such as is in Table 1, the plot of which is in Figure 1. The second column in Table 1 contains the corrected and averaged travel-time from the shot-point ($h=0$) to each of various depths below this datum, with the shot-point 1000 feet from the well-head.

If the horizontal distance from the shot-point to the well-head is indicated by d, the travel-time from the shot-point to a depth h in the well is

$$(1) \qquad t = 1/a \cosh^{-1} \left[1 + a^2(d^2 + h^2)/2v_o(v_o + ah)\right]. \text{ (Slotnick, 1936)}$$

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For our purposes we rewrite this formula in the form

$$v_o = ah/2\left[\sqrt{\left[1 + 2\left[(d/h)^2 + 1\right]/(\cosh at - 1)\right]} - 1\right] \tag{2}$$

and our problem is to determine the constants v_o and a in this equation from the data of Table 1. For this purpose, two observations are theoretically sufficient.

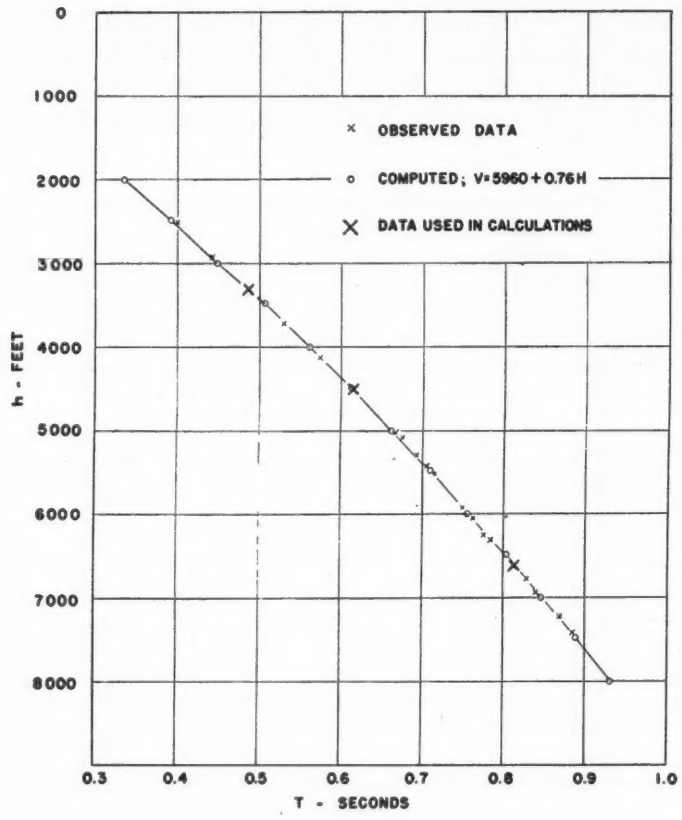

FIG. 1

For practical purposes, however, it is better to take three sets of data, suitably spaced, and use the average of the three results obtained, as will be indicated in the succeeding paragraphs.

Suppose that we decide, by observation, to use the following three sets of data:

TABLE 2

1. $d=1000$	$h=3328$	$t=0.485$
2. $d=1000$	$h=4528$	$t=0.614$
3. $d=1000$	$h=6626$	$t=0.813$

In Figure 1, these are indicated by the larger crossed points. We then consider the values $a=0.5$, 0.6, 0.7, 0.8 and 0.9, since we know from experience that the proper value will fall somewhere within this range. For each set of chosen data of Table 2 and for each of these values of a, we compute the corresponding value of v_0 by relation (2), and the results are listed in Table 3. These results, in turn, are

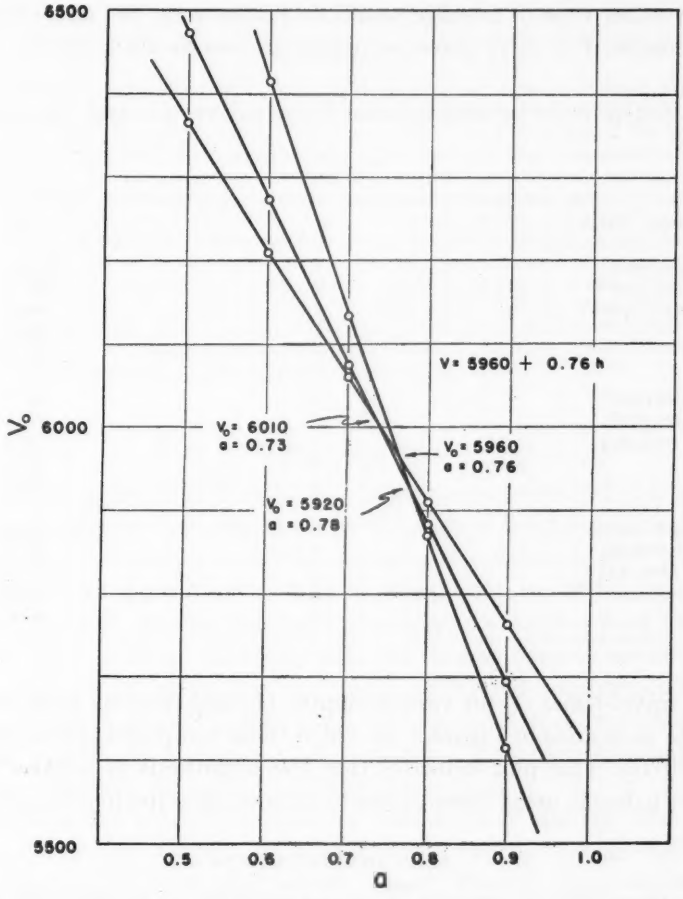

FIG. 2

plotted in Figure 2 in which there are three intersections, each curve intersecting the other two. In the ideal case, of course, all these three curves would be concurrent. However, in the practical cases we shall have a situation as in Figure 2 with the "degree of fit" determined to some extent by the spacing of the three points of intersection.

In our particular case in which we assume "three-point" accuracy, the intersections are seen to be

(0.733, 6010), (0.763, 5960), (0.780, 5920).

It is best here to average the a's separately and the v_o's separately, obtaining in this way for our result:

$$v_o = 5960$$
$$a = 0.76.$$

Almost any other type of average would do just as well, but obtaining it would not be so simple. For three-place accuracy our results are accurate enough for the purpose.

The next step in the process is to use these values of v_o and a in equation (1),

TABLE 3

Data from Table 2	a	v_o
$d=1000$	.5	6365
$h=3328$	.6	6210
$t=0.485$	.7	6060
	.8	5910
	.9	5765
$d=1000$	.5	6475
$h=4528$	.6	6275
$t=0.614$	.7	6075
	.8	5885
	.9	5695
$d=1000$	.5	6695
$h=6626$	.6	6415
$t=0.813$	.7	6135
	.8	5870
	.9	5615

obtaining travel-times (t) for various depths (h) and plotting them with the observed data as is done in Figure 1, in which these computed points are indicated by open circles. This plot indicates that the hypothesis of a linear increase of velocity with depth, using these values for v_o and a, is a justifiable and a good one.

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QUANTITATIVE INTERPRETATION OF VERTICAL MAGNETIC ANOMALIES OVER VEINS*

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ABSTRACT

By using ordinary magnetic induction methods of analysis, Haalck, Heiland, and others have developed formulas which express the magnetic anomaly over a vertical or inclined vein of tabular shape as a function of the susceptibility, dimensions, shape, and disposition of the vein, and of the strength and direction of the earth's magnetic field. On the basis of these fundamental formulas, other formulas for the vertical component of the magnetic field are derived in the present paper for such veins in intermediate northern magnetic latitudes. Special emphasis is given to the orientation of the veins relative to the magnetic north direction. Several families of vertical magnetic intensity curves for veins with different strikes and dips are given. All theoretical curves for veins striking magnetic north are plotted in terms of a parametric unit so that, once plotted, they can be used repeatedly in different districts, provided a proper multiplying factor is chosen for the observed curve. The importance of the transverse horizontal magnetization effect under certain conditions of orientation is demonstrated. It is shown mathematically that small vertical magnetic anomalies are to be expected for thin veins striking east and dipping south at an angle equal to, or approximately equal to, the complement of the angle of magnetic inclination.

INTRODUCTION

According to a theorem of Poisson, the magnetic potential of a body is proportional to the gravity component in the direction of magnetization. This fundamental relation between the magnetic and gravitational properties of a body has greatly aided the interpretation of magnetic anomalies. In particular it has helped in those cases where ordinary methods of magnetic induction may be applied to the solution of a problem. In such cases the torsion balance formulas, derived from Newton's law of gravitation, are readily converted into formulas which can be used to calculate magnetic anomalies. As torsion balance formulas have been derived for several typical geological structures, the corresponding magnetic formulas are available for analysis of these structures.

Formulas for the vertical magnetic anomalies over tabular veins have been developed by Haalck (1930), Heiland (1940), Smyth (1899), Rothé (1930), Rossiger (1932), Duhoux (1938), Jakosky (1940), Evrard (1943), de Magnée and Raynaud (1944), Koulomzine and Massé (1947). A review of this literature shows that each of these authors has given formulas that apply to special cases only, and has chosen these cases for discussion. For example, Smyth gives formulas for veins striking magnetic north. Duhoux, and also Koulomzine and Massé, give formulas for veins of infinite depth extent.

Accordingly, it seems desirable at this time to present in comprehensive form formulas and intensity curves that apply to both the special cases and cases of a

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more general nature. Consideration is given to those geological structures which take the form of tabular-shaped vertical or inclined dikes, fissure veins, or replacement veins or pods.

MAGNETIC INDUCTION METHOD OF ANALYSIS

Assumptions

Formulas can express the magnetic intensity over a body as a function of the susceptibility, shape, dimensions, and disposition of the body, and of the strength and direction of the earth's magnetic field. In their derivation and use, several assumptions are made.

(1) The ordinary theory assumes that the body is uniformly magnetized, and disregards the effects of flux concentration on edges and corners of the body.

(2) The theory does not include the demagnetization effects produced by the existence of the body in the magnetic field of the earth.

(3) The formulas considered in this discussion apply to two-dimensional bodies, whose length in the direction of strike is infinite. Consideration is given to only those veins whose depth extent greatly exceeds the width and whose depth of cover is not less than half the width. When reference is made to a "finite vein," the vein is still considered infinite in length, but finite in depth extent.

(4) In computing the magnetic susceptibility of an ore body whose accompanying anomaly is caused wholly by the mineral magnetite in the ore, it is assumed that the susceptibility is proportional to the amount of magnetite by volume contained in the ore (Slichter, 1929).

(5) The statements and conclusions apply to results obtained in the northern hemisphere at intermediate magnetic latitudes.

(6) It is assumed that no anomalous polarization effects are produced by the bodies.

(7) Unless stated to the contrary, all directions of strike or dip to which reference is made are magnetic directions. For example, a body "striking north" means "striking magnetic north."

Notations

Alpha is the angle measured horizontally westward, counterclockwise from above, from the direction of magnetic north to the direction of strike of the vein (Fig. 1). For convenience the values of α are confined between 0 and π. For veins striking magnetic north, $\alpha=0$; for veins striking magnetic east, $\alpha=\pi/2$.

Delta is the angle measured vertically upward, counterclockwise from the north or east, from a horizontal line to the 4-3 face constituting the side of the vein. For veins dipping west or south, $\delta<\pi/2$; for vertical veins $\delta=\pi/2$; for veins dipping east or north, $\delta>\pi/2$.

The radial distances from the observation point P to the four corners, 1, 2, 3, and 4, respectively, of the cross-sectional parallelogram as measured in a vertical plane perpendicular to the strike of the vein are denoted by r_1, r_2, r_3, and r_4.

The angles of depression, in radians, measured in a clockwise direction from the horizontal line AA' to the same four corners, 1, 2, 3, and 4, are denoted respectively by ϕ_1, ϕ_2, ϕ_3, and ϕ_4. For veins of great depth extent, $r_2=r_4$ approximately, and $\phi_2=\phi_4$ approximately.

The direction of the theoretical magnetic profile AA' is taken at right angles to the strike of the vein. The A' end of the profile lies due magnetic east of the vein for $\alpha=0$, northeast of the vein for $0<\alpha<\pi/2$, due north of the vein for $\alpha=\pi/2$, and northwest of the vein for $\pi/2<\alpha<\pi$.

H_0 and Z_0 are, respectively, the horizontal and vertical components of the earth's normal magnetic field in the area.

k is the excess of the magnetic susceptibility of the vein over that of the adjacent rock. Although it may be either positive or negative in sign, in this paper k is assumed positive, as the susceptibility of the vein is assumed to be greater than that of the adjacent rock.

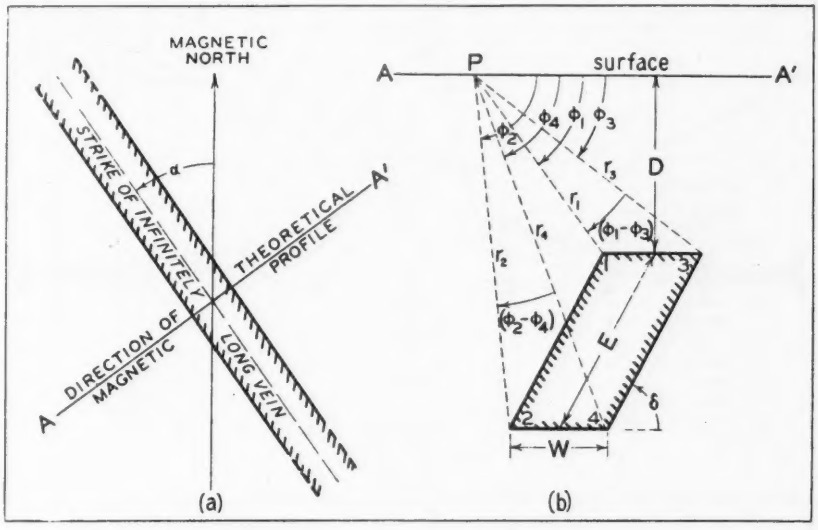


FIG. 1. Diagrammatic plan (a) and vertical section (b) through an infinitely long vein, showing angles and distances involved in theoretical computations.

General formula

To obtain the magnetic intensity for an infinitely long inclined vein as shown in Figure 1, the difference between the magnetic effects of two slopes is used. The formula for the vertical intensity over an inclined medium is taken from Heiland's text (1940). On the basis of the previous assumptions and notations, the vertical component of the magnetic intensity at point P for an inclined vein (Fig. 1) is given by

$$\Delta Z = 2k \sin \delta [(H_o \sin \alpha \sin \delta + Z_o \cos \delta) \log_e r_2 r_3 / r_1 r_4 - (H_o \sin \alpha \cos \delta - Z_o \sin \delta)(\phi_1 - \phi_2 - \phi_3 + \phi_4)]. \quad (1)$$

Units and scales

In order that a single set of theoretical curves may be used repeatedly, it is preferable to plot the magnetic intensity over all the theoretical bodies in the same units. This procedure permits a comparison of the true relative magnitudes

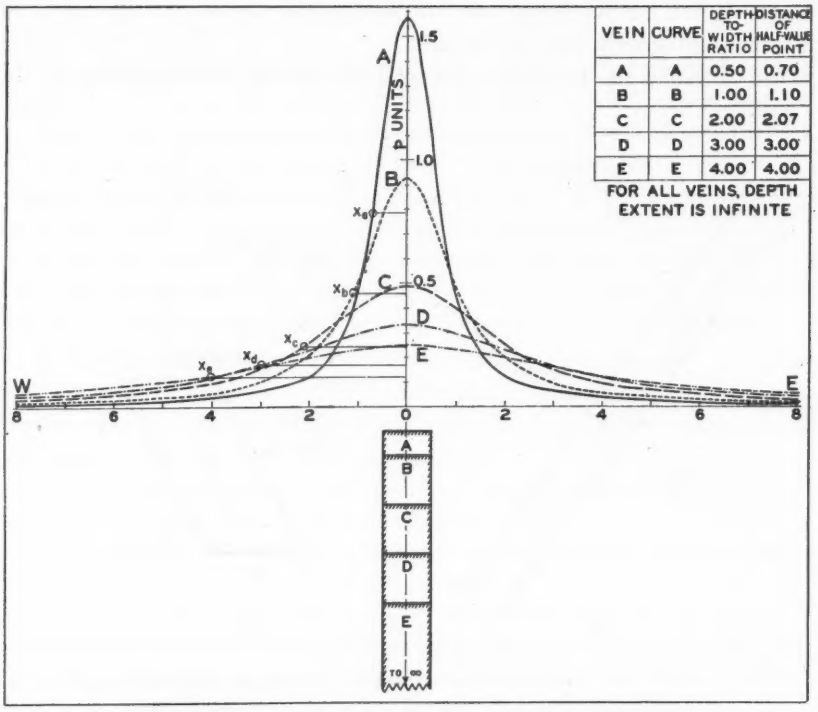


FIG. 2. Vertical magnetic intensity over infinite vertical veins striking north, showing effect of depth-to-width ratio. For all veins, depth extent ∞.

of the intensity caused by bodies of different dimensions and dispositions. To clarify this statement, let us consider a vertical vein striking north and of infinite depth extent (Fig. 2). In this case formula (1) reduces to

$$\Delta Z = 2kZ_o(\phi_1 - \phi_3). \quad (2)$$

We may write

$$p = 2kZ_o \quad (3)$$

so that ΔZ is proportional to p, which is, therefore, a parameter determined by the value Z_o for the district and the value of k, the susceptibility excess, for the

body. If the only magnetic constituent of the ore body is magnetite, k, and therefore p, will vary with the magnetite content. The parameter p unit is used as a standard unit of intensity for all curves in this paper.

The chart in Figure 3 may be used conveniently to convert units of p into units of gammas for different susceptibilities and magnetite contents.* In order to compare an observed intensity curve with a theoretical intensity curve, it is convenient to convert the observed curve into the same standard p units as the theoretical curve when the horizontal distances are made to agree. The factor by

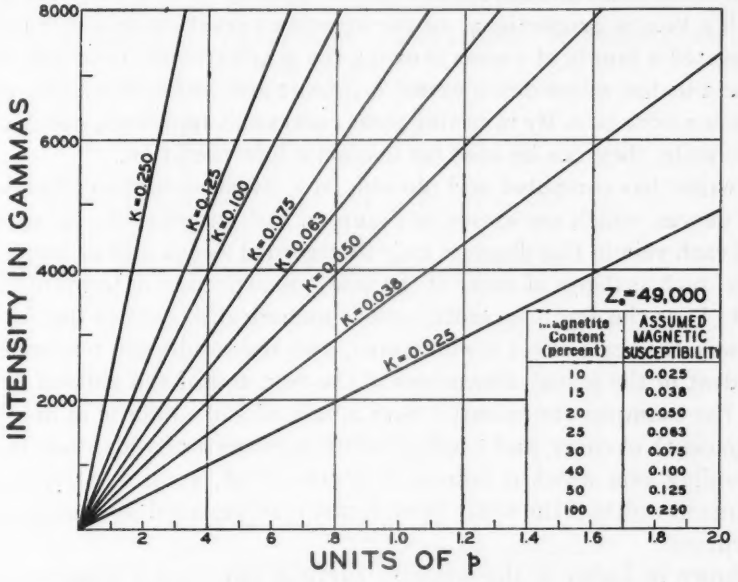


FIG. 3. Chart to convert gammas into units of p for different susceptibilities and obtain multiplying factor for the observed intensity curve.

which the values of the observed curve must be multiplied is p'/T, where T is the maximum value of the observed curve and p' is the p-unit equivalent of this maximum value as obtained from Figure 3. As the value of Z_0 is in general different for each district, a new chart similar to that in Figure 3 must be computed and plotted for each district. If it is known that in a certain district the susceptibility of 100 per cent magnetite is different from the assumed value of 0.25, another table similar to that in the lower right-hand corner of Figure 3 can be computed readily and employed for the conversion of magnetite content to assumed susceptibility. This procedure changes merely the absolute value of the parameter p

* The susceptibility of pure magnetite is tentatively assigned a value of 0.25 because of the success that has been obtained to date by using this value for the magnetite in replacement iron-ore bodies in the Iron Springs district, Utah. Studies are still in progress, however, to ascertain whether this value can be used throughout the whole district. On the basis of this assumption, the assumed susceptibility of an ore containing 10 per cent magnetite by volume is 0.10×0.25, or 0.025.

unit for any given magnetite content and hence the multiplying factor for the observed field curve. It does not affect the theoretical curves.

VERTICAL MAGNETIC INTENSITY CURVES FOR VERTICAL VEINS

Infinite vertical veins striking north

Equation (2) applies to infinite vertical veins striking north. As this formula is of the same form as the negative curvature formula in torsion balance theory for a vein of the same dimensions and disposition, the vertical magnetic intensity over such a vein is proportional to the negative curvature values. Shaw (1932) has calculated a family of curves showing the gravitational curvature values for 14 different bodies whose depth extent is infinite and whose depth-to-width ratio varies from 0.05 to 20.0. By inverting these curves and applying a suitable vertical magnetic scale, they can be used for magnetic interpretation.

The writer has computed and plotted, on a larger scale than Shaw's, several of these curves, which are shown in Figure 2. For purposes of convenience, the width of each vein in this diagram may be regarded as our unit of length, and all distances, such as depth of cover of the vein, are expressed in terms of this width as a unit. Thus the depth-to-width ratio is numerically equal to the depth itself. In this way the scale effect is eliminated, and the results are rendered entirely independent of the actual dimensions of the vein and of the units of length employed. For example, the intensity over a vein which is infinite in depth extent, 2 units in depth of cover, and 1 unit in width is theoretically identical to that of a corresponding vein which is infinite in depth extent, 4 units in depth of cover, and 2 units in width, if the width in each case is represented by the same distance on the curve.

As shown in Figure 2, the intensity curve in each case is symmetrical about the center line of the vein. All values are positive and the curve approaches the x-axis asymptotically. The curves show qualitatively that the amplitude of each curve decreases rapidly with increasing depth of cover of the vein. Figure 4 shows this effect quantitatively by plotting the maximum value against the depth-to-width ratio. The maximum values decrease rapidly as the depth-to-width ratio increases to about 8 or 10, beyond which the decrease becomes more gradual.

On each of the curves in Figure 2 is shown the distance of the half-value point, which is defined as that horizontal distance between the center line of the vein to the point on the intensity curve where the value is one half of the maximum. The abscissa of each of the half-value points is indicated as follows: x_a for Curve A, x_b for Curve B, etc. For all depths greater than one unit the distance of the half-value point is for all practical purposes equal to the depth of cover of the body. In the case of a shallower vein, however, this approximation is less accurate, the error increasing with the shallowness of the vein. The error in estimating the depth of the vein in this way is about 3 per cent at a depth of 2 units, 10 per cent at a depth of one unit, and 40 per cent at a depth of 0.5 unit.

It is inadvisable to use this means of estimating depths for veins whose depth of cover is less than one unit.

Finite vertical veins striking north

For finite vertical veins striking north equation (1) reduces to

$$\Delta Z = 2kZ_o(\phi_1 - \phi_2 - \phi_3 + \phi_4). \tag{4}$$

Comparison of veins of different depth extents.—For a vein of finite depth extent, as shown in equation (4), the effect of the bottom face is to diminish the intensity over an otherwise infinitely deep vein by an amount which depends on the depth extent of the vein (Fig. 5). The intensity curve crosses the x-axis to reach a mini-

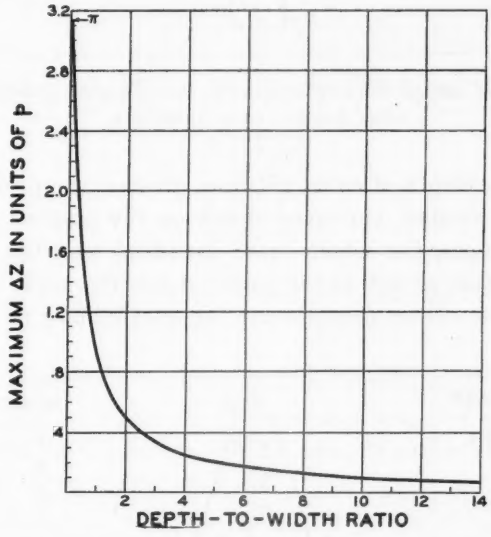
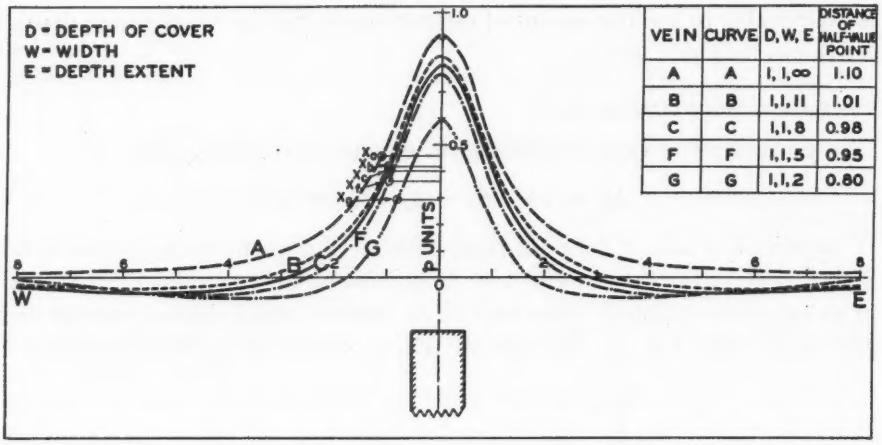


FIG. 4. Relation between maximum value of ΔZ and depth-to-width ratio for infinite vertical veins striking north.

mum on either side of the center line. As the depth extent becomes smaller, the positive amplitude becomes smaller, the value of the negative minima becomes numerically larger until it reaches a maximum value, after which it decreases, and the points where the curve crosses the x-axis, as well as the points of minima, move in nearer to the center line of the vein. Though the rule that the depth to the top of the body is equal to the distance of the half-value point still holds approximately for bodies of large depth extent, provided the usual precautions of depth-to-width ratios are observed, the rule usually fails for bodies of small depth extent. In general it is unsafe to employ the rule for vertical bodies of finite depth extent.

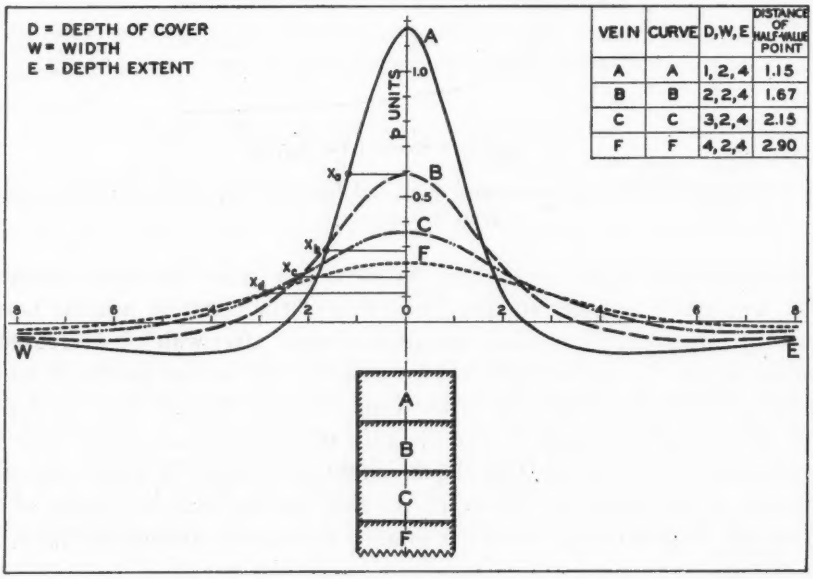
Comparison of veins of different depths of cover.—Figure 6 shows the effect of depth of cover on the intensity curve for finite veins having the same width and



VEIN	CURVE	D, W, E	DISTANCE OF HALF-VALUE POINT
A	A	1, 1, ∞	1.10
B	B	1, 1, 11	1.01
C	C	1, 1, 8	0.98
F	F	1, 1, 5	0.95
G	G	1, 1, 2	0.80

FIG. 5. Intensity over vertical veins striking north, showing effect of depth extent. For all veins, depth of cover 1, width 1.

depth extent. As the depth of cover becomes greater, the positive and negative amplitudes become smaller, the steep slopes on the positive part of the curve change to gentle slopes, the whole curve broadens, and the points where the curve crosses the x-axis, as well as the points of minima, move farther away from the center line. These curves demonstrate the unreliability of using the distance



VEIN	CURVE	D, W, E	DISTANCE OF HALF-VALUE POINT
A	A	1, 2, 4	1.15
B	B	2, 2, 4	1.67
C	C	3, 2, 4	2.15
F	F	4, 2, 4	2.90

FIG. 6. Intensity over finite vertical veins striking north, showing effect of depth of cover. For all veins, width 2, depth extent 4.

of the half-value point as a measure of depth in the case of bodies of small depth extent.

Comparison of veins of different widths.—Figure 7 shows the effect of width on

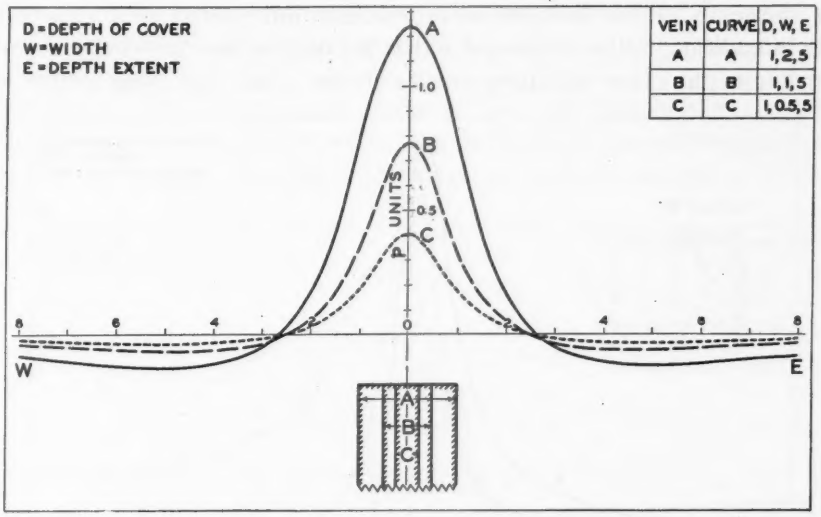


FIG. 7. Intensity over finite vertical veins striking north, showing effect of width. For all veins, depth of cover 1, depth extent 5.

the intensity curve for finite veins having the same depth of cover and depth extent. As the width increases, the positive and negative amplitudes increase, and the points where the curve crosses the x-axis, as well as the points of minima, move slightly away from the center line.

Infinite vertical veins striking east

For infinite vertical veins striking east equation (1) reduces to

$$\Delta Z = 2kZ_o[H_o/Z_o \log_e (r_3/r_1) + (\phi_1 - \phi_3)]. \tag{5}$$

Curve A in Figure 8 is the intensity curve for such a vein. The value of H_o/Z_o is taken for convenience as 0.58, which corresponds with the magnetic values in an area where the magnetic inclination is 60°, such as Florence, Arizona. The curve is asymmetrical. On its south side the curve is at first steep and then gentle on its flanks, where it approaches the x-axis asymptotically from above the x-axis. On its north side the curve is very steep, crosses the x-axis, and reaches a minimum. The maximum point lies south of the center line of the vein.

The asymmetrical nature of this curve is due solely to the transverse horizontal magnetization effect, which is expressed in the term $(H_o/Z_o \log_e r_3/r_1)$ in equation (5). As will be shown below, the intensity formulas for all veins whose strike is different from north generally contain the term $\log_e r_3/r_1$ for the infinite

vein or $\log_e r_2r_3/r_1r_4$ for the finite vein. Except in areas of high magnetic latitude, where H_o/Z_o is small, or for thin veins, in which case $\log_e r_3/r_1$ and $\log_e r_2r_3/r_1r_4$ are small, the transverse magnetization term cannot be neglected for such bodies. If the transverse magnetization effect were not considered, the asymmetrical curve shown in Figure 8 would be erroneously interpreted as a vein dipping south. In addition, failure to recognize that the peak of the curve lies south of the center line might cause the interpreter to choose a test hole lying farther south

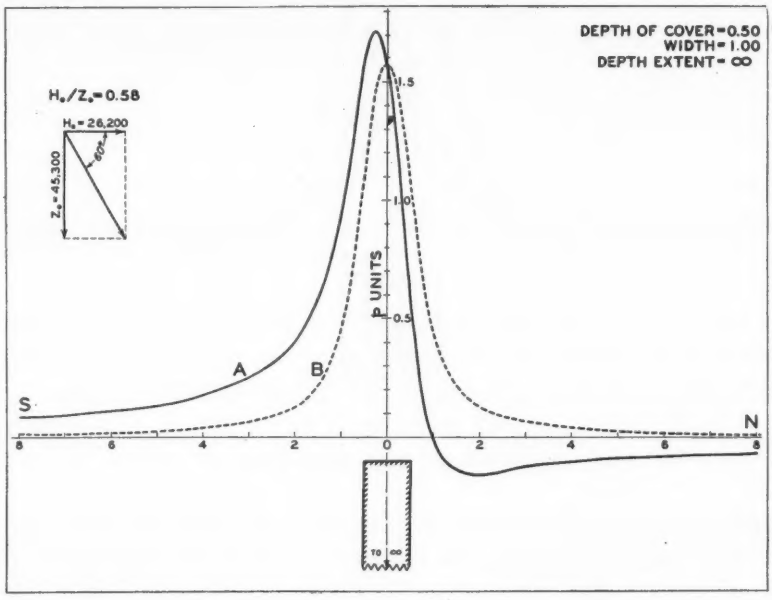


FIG. 8. Intensity over infinite vertical vein striking east (Curve A), and similar vein striking north (Curve B). Magnetic inclination 60°.

than it should be. To show the pronounced transverse magnetization effect in the example given, the intensity curve for a corresponding vertical vein striking north is included in the same figure (Curve *B*).

Finite vertical veins striking east

For finite vertical veins striking east equation (1) becomes

$$\Delta Z = 2kZ_o[H_o/Z_o \log_e r_2r_3/r_1r_4 + (\phi_1 - \phi_2 - \phi_3 + \phi_4)]. \tag{6}$$

Curve *A* in Figure 9 is the intensity curve for such a vein. The curve is asymmetrical, and the same generalizations about the maximum, slopes, and minima apply as in the case of the infinite vein with similar orientation. However, as the lower face becomes effective, the curve crosses the x-axis on the south as well as on the north, and reaches a minimum. If the transverse magnetization were not considered, an observed curve of this shape might lead to the erroneous interpretation of an inclined vein of southerly dip.

Vertical veins striking neither north nor east

For vertical veins whose strike is nearly meridional, the transverse magnetization may be neglected, and the above analysis for veins striking north may be employed. The higher the magnetic latitude, the greater is the departure from magnetic meridian which may be permitted before the transverse magnetization must be considered.

For vertical veins whose strike is nearly east, the intensity obtained for a similar vein striking exactly east, which includes the full transverse magnetization effect, may be assumed. The higher the magnetic latitude, the greater is the de-

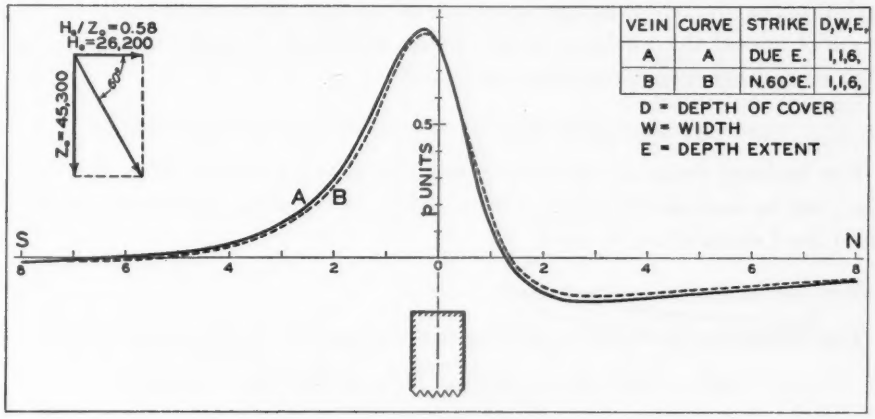


FIG. 9. Intensity over finite vertical vein striking east (curve A), and similar vein striking 30° from east (curve B). Magnetic inclination 60°.

parture from east which may be permitted before a more rigorous analysis must be considered.

When the more rigorous analysis is used, the anomaly for a vertical vein of finite depth extent, obtained from formula (1), becomes

$$(7) \qquad \Delta Z = 2kZ_o[H_o/Z_o \sin \alpha \log_e r_2r_3/r_1r_4 + (\phi_1 - \phi_2 - \phi_3 + \phi_4)].$$

As the formula involves $\sin \alpha$, in general there are two values of α, namely α and $(\pi - \alpha)$, which will produce the same intensity curve. Curve B in Figure 9 is the intensity curve for such a vein, in which $\alpha = 120°$, corresponding to a strike of magnetic N. 60° E. The same intensity curve would be obtained for a similar vein for which α is 60°, corresponding to a strike of magnetic N. 60° W. The curve is not greatly unlike Curve A of the same figure, which is for a similar vein with a strike of due magnetic east. As the departure from due magnetic east becomes greater than 30°, which means that α is greater than 120°, the intensity curve continues to approach a symmetrical curve whose point of maximum lies directly over the center line of the vein. A truly symmetrical curve is not obtained until $\alpha = 180°$.

For a vertical vein of infinite depth extent the anomaly is

$$\Delta Z = 2kZ_o[H_o/Z_o \sin \alpha \log_e r_3/r_1 + (\phi_1 - \phi_3)]. \tag{8}$$

In general there are similarly two values of α, namely α and $(\pi-\alpha)$, which produce the same intensity curve. The intensity curves for veins in this class are intermediate between the symmetrical type of curves obtained for veins striking north and the asymmetrical type obtained for veins striking east. On its south side the curve does not cross the x-axis. As the departure from a due east direction is increased so that the strike becomes more nearly either due north or due south, the intensity curve continues to approach a symmetrical curve whose point of maximum lies directly over the center line of the vein. In doing so the point where the curve crosses the x-axis on its north side, as well as the point of minima on its north side, move away from the center line.

VERTICAL MAGNETIC INTENSITY CURVES FOR INCLINED VEINS

For inclined veins of very steep dip the above analysis given for vertical veins may be used satisfactorily. Often, however, formulas developed specifically for inclined veins must be used.

Infinite inclined veins striking north

For infinite inclined veins striking north equation (1) becomes

$$\Delta Z = 2kZ_o \sin \delta[\cos \delta \log_e r_3/r_1 + \sin \delta(\phi_1 - \phi_3)]. \tag{9}$$

As this formula is of the same form as the negative curvature formula in torsion balance theory for a vein of the same character, the magnetic intensity over such a vein is proportional to the negative curvature values. Shaw (1932) has calculated several families of curves showing the gravitational curvature values for 50 bodies whose depth-to-width ratio varies from 0.1 to 2.0 and whose angle of dip varies from 10° to 90°. By inverting these curves and applying a suitable vertical magnetic scale, they can be used for magnetic interpretation.

Figure 10 shows the intensity curves for veins with various easterly dips. The intensity curve for a vertical vein of the same depth-to-width ratio is shown in the same figure for comparison. In each case the depth of cover is half a unit and the width of the top face of the vein is one unit. Though it is convenient to use the width of the top face as one of the dimensions of an inclined vein, it should be noted that this width is larger than the thickness of the vein in a direction perpendicular to the direction of dip.

The intensity curves for such inclined veins are asymmetrical. On its down-dip or right side each curve has a comparatively gentle slope and approaches the x-axis asymptotically from points lying above the x-axis; the curve does not cross on this side. On its up-dip or left side the curve is steep and crosses the x-axis to reach a minimum. As the dip of the vein decreases, the positive amplitude decreases except in the case of very shallow veins (Shaw, 1932), the negative ampli-

tude becomes larger up to a maximum value, after which it decreases, and both the points of maximum and minimum, as well as the point where the curve crosses the x-axis, shift farther to the right in the direction of dip. The decrease in the positive amplitude with decreasing dip is accentuated by the fact that the thickness of the vein must be progressively diminished in order to keep the width of the top face the same in each case. For such veins of infinite depth extent K. Jung (1927) has shown that the intensity value over the midpoint of the upper

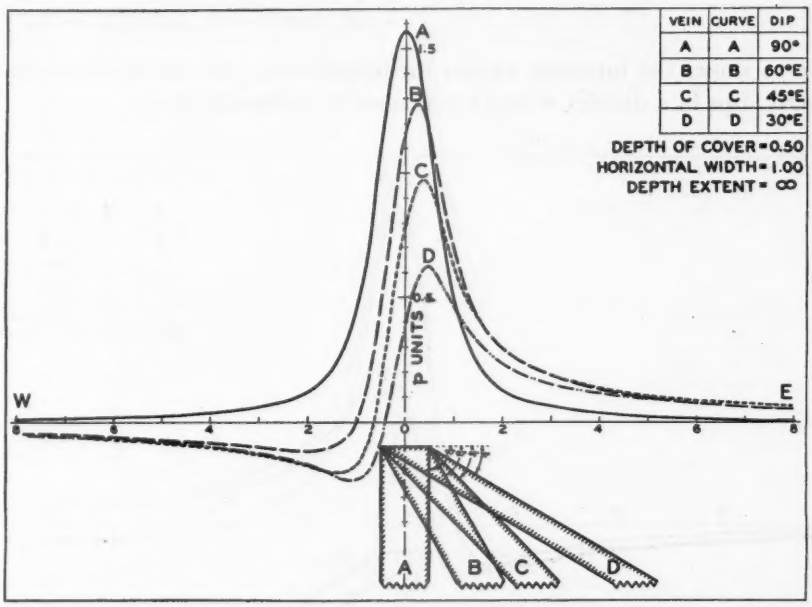


FIG. 10. Intensity over infinite inclined veins striking north and dipping 30° E., 45° E., 60° E., 90°. For all veins, depth of cover 0.5, horizontal width 1.

face is equal to the algebraic sum of the positive maximum and the negative minimum values.

Finite inclined veins striking north

For finite inclined veins striking north equation (1) becomes

$$\Delta Z = 2kZ_o \sin\delta\left[\cos\delta \log_e r_2r_3/r_1r_4 + \sin\delta(\phi_1 - \phi_2 - \phi_3 + \phi_4)\right]. \tag{10}$$

In Figure 11 the intensity curves over finite veins with dips of 60° and 30°, respectively, are compared with the intensity curves for corresponding infinite veins. The asymmetry of the curves for the finite veins is not as pronounced as that for the corresponding infinite veins. On its down-dip or right side each of the curves for the finite veins crosses the x-axis, which is not so in the case for infinite veins.

In the case of inclined veins striking north, a curve plotted for a vein of

easterly dip may be used for a similar vein of westerly dip merely by turning the curve through 180°, so that the gentle slope of the curve corresponds to the down-dip side of the body.

Infinite inclined veins striking east

For infinite inclined veins striking east equation (1) becomes

$$\Delta Z = 2k \sin\delta\left[(H_o \sin\delta + Z_o \cos\delta)\log_e r_3/r_1 - (H_o \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_3)\right]. \tag{11}$$

Figure 12 shows the intensity curves for infinite veins of various southerly and northerly dips in a district where the magnetic inclination is 60°.

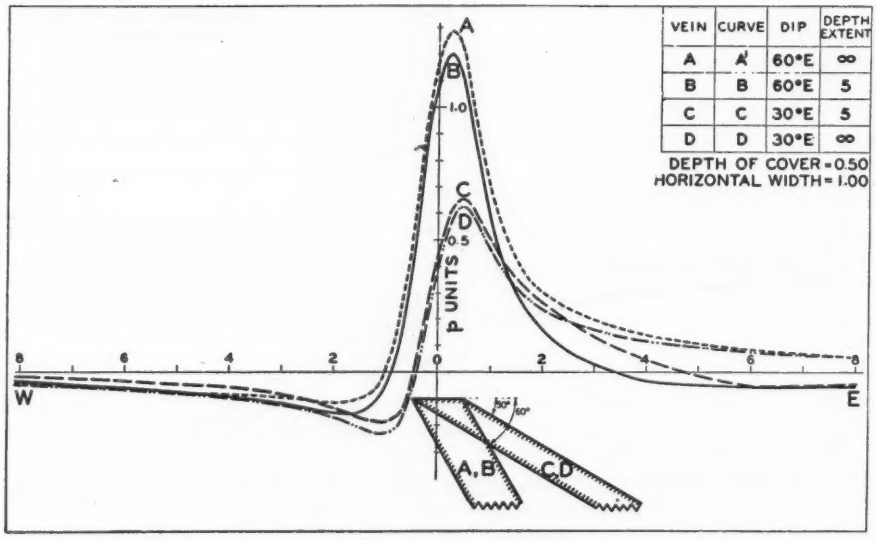


FIG. 11. Intensity over finite inclined veins striking north (veins B and C), and infinite veins with same orientation (veins A and D) included for comparison. For all veins, depth of cover 0.5, horizontal width 1.

For an infinite vein dipping north at an angle less than the angle of magnetic inclination of the district, the intensity curve is asymmetrical. (See Curve *D* in Fig. 12c and Curve *B* in Fig. 12b.) On the north or down-dip side of the maximum the curve slopes gently northward and approaches the x-axis asymptotically from points lying above it. On the south or up-dip side the curve is steep, and crosses the x-axis to attain a minimum that is not pronounced. The point of maximum lies north of the center of the top face projected vertically to the surface.

For an infinite vein dipping north at an angle equal to the angle of magnetic inclination, a special case arises. In this case (vein *C* in Fig. 12a) $\tan\delta = \sin\delta/\cos\delta = -Z_o/H_o$ ($\tan\delta$ is negative because $\pi/2 < \delta < \pi$), from which we obtain $(H_o \sin\delta + Z_o \cos\delta) = 0$. Using the identity $\sin^2\delta + \cos^2\delta = 1$, it follows that

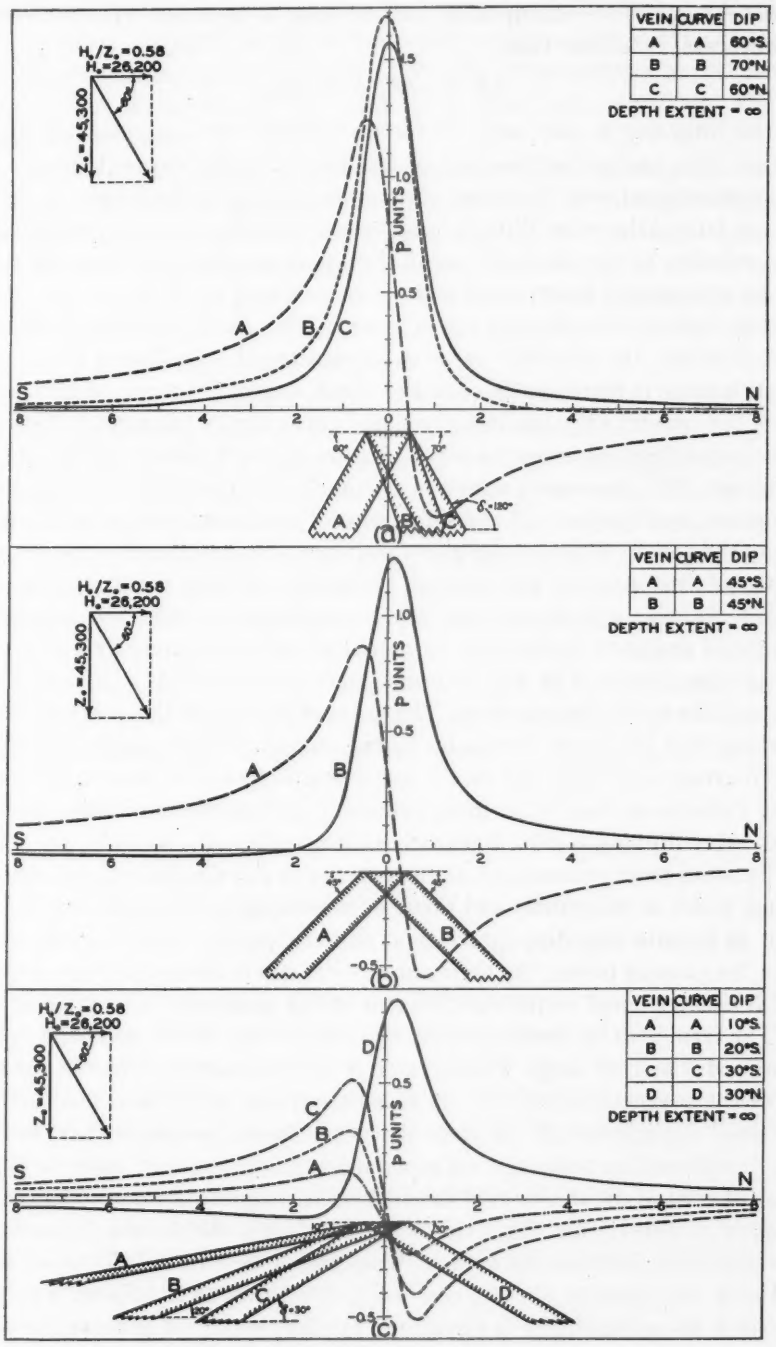


FIG. 12. Intensity over infinite inclined veins striking east. For all veins, depth of cover 0.5, horizontal width 1, magnetic inclination 60°.

$(H_o \cos \delta - Z_o \sin \delta) = -Z_0/\sin \delta$. By substituting in equation (11) the two terms in parentheses, it follows that

$$\Delta Z = 2kZ_o(\phi_1 - \phi_3). \tag{12}$$

Thus the intensity is the same as for an infinite vertical vein striking north (equation (2)), and is independent of H_o. The intensity curve (Curve *C* in Fig. 12a) is symmetrical, with the point of maximum lying vertically above the center of the top face of the vein. Without proper consideration of the orientation of the vein in relation to the magnetic north direction, an observed curve of this type might be erroneously interpreted as a vertical vein.

For an infinite vein dipping north at an angle greater than the angle of magnetic inclination, the intensity curve is asymmetrical. (See Curve *B* in Fig. 12a.) The south slope is more gentle than the north slope. The point of maximum lies south of the center of the top face projected vertically to the surface. On its south side the curve does not cross the x-axis; but on its north side it crosses and attains a minimum. With increasing angles of northerly dip, the minimum becomes more pronounced, and the point of crossing, point of minimum, and point of maximum move to the south. When the angle of northerly dip reaches a value of 90°, or is close to 90°, the analysis for vertical, or nearly vertical, veins applies (Fig. 8).

For an infinite vein dipping south at an angle greater than the complement of the angle of magnetic inclination (sub-critical dip), the intensity curve is asymmetrical. (See Curve *A* in Fig. 12a and curve *A* in Fig. 12b.) The south slope is gentle and the north slope is steep. The point of maximum lies south of the center of the top face projected vertically to the surface. On its south side the curve does not cross the x-axis; but on its north or up-dip side it crosses the x-axis and attains a minimum that is far more pronounced than the minimum observed for similar veins dipping north. With decreasing angles of southerly dip, the minimum becomes more pronounced at the expense of the maximum, and the point of crossing, point of minimum, and point of maximum move to the south.

For an infinite vein dipping south at sub-critical dip, a special case arises. As used in the present paper, the term sub-critical dip is defined as that angle of dip which is exactly equal to the complement of the magnetic inclination in the district. The term is to be distinguished from critical dip, which has been defined by Stearn (1929) as that angle whose value is approximately equal to the complement of the magnetic inclination in the district and whose exact value must be determined experimentally in each district. Stearn contends that, because of nearly compensating polarities, an eastward-striking ore body lying at depth and dipping at critical dip might give no observable magnetic anomaly. In case a vein is dipping at sub-critical dip (vein *C* in Fig. 12c), $\tan \delta = \sin \delta/\cos \delta = H_o/Z_o$ ($\tan \delta$ is positive because $0 < \delta < \pi/2$, from which we obtain $(H_o \cos \delta - Z_0 \sin \delta) = 0$. Using the identity $\sin^2 \delta + \cos^2 \delta = 1$, it follows that $(H_o \sin \delta + Z_0 \cos \delta) = H_0/\sin \delta$. By substituting in equation (11) the two terms in parentheses, it follows that

$$\Delta Z = 2kH_o \log_e r_3/r_1. \tag{13}$$

The positive part of the intensity curve, with a gentle south slope and steep north slope, is an exact, inverted image of the negative part of the curve, whose negative amplitude is equal to the positive amplitude of the positive part (Curve *C* in Fig. 12c*). The curve crosses the x-axis at a point lying vertically above the center of the top face.

It is obvious from equation (13) that in areas lying at high magnetic latitudes, where H_o is small, the magnitude of the intensity will be correspondingly small for thin veins dipping at or near sub-critical dip. Such veins might give no observable vertical magnetic anomaly. In areas lying at intermediate magnetic latitudes, such veins might give little or no observable vertical magnetic anomaly. In any event, if the existence of such veins is suspected in an area, additional precautions in interpretation are necessary.

For an infinite vein dipping south at an angle less than the angle of sub-critical dip, the general shape of the curve is somewhat similar to that for sub-critical dip (Curve *B* in Fig. 12c). However, the negative amplitude is greater than the positive amplitude, and the curve crosses the x-axis at a point lying south of the center of the top face projected vertically to the surface. With decreasing angles of southerly dip, the point of crossing, point of maximum, and point of minimum move to the south. For small angles of southerly dip the negative amplitude becomes pronouncedly larger than the positive amplitude (Curve *A* in Fig. 12c). Under such conditions of dip it is conceivable that in plan view on a magnetic map a thin vein of finite length striking in an easterly direction might exhibit a rather pronounced negative center on its up-dip (north) side and, in comparison, a numerically smaller positive center on its down-dip (south) side.

Finite inclined veins striking east

For finite inclined veins striking east equation (1) becomes

$$\Delta Z = 2k \sin\delta\left[(H_o \sin\delta + Z_o \cos\delta)\log_e r_2 r_3/r_1 r_4 - (H_o \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_2 - \phi_3 + \phi_4)\right]. \tag{14}$$

Figure 13 shows the intensity curves for finite veins of various southerly and northerly dips in a district where the magnetic inclination is 60°.

For a finite vein dipping north at an angle less than the angle of magnetic inclination (Curve *B* in Fig. 13b), the same general intensity features obtain as for the infinite vein of similar orientation, except that the north flank of the curve crosses the x-axis.

For a finite vein dipping north at an angle equal to the angle of magnetic inclination, a special mathematical case arises. By using the same mathematical relations as used above for the infinite vein, it follows that in this case the intensity over the finite vein becomes

$$\Delta Z = 2kZ_o(\phi_1 - \phi_2 - \phi_3 + \phi_4). \tag{15}$$

* Though independent of Z_o, the curve is given in units of p (i.e., $2kZ_o$) for comparison.

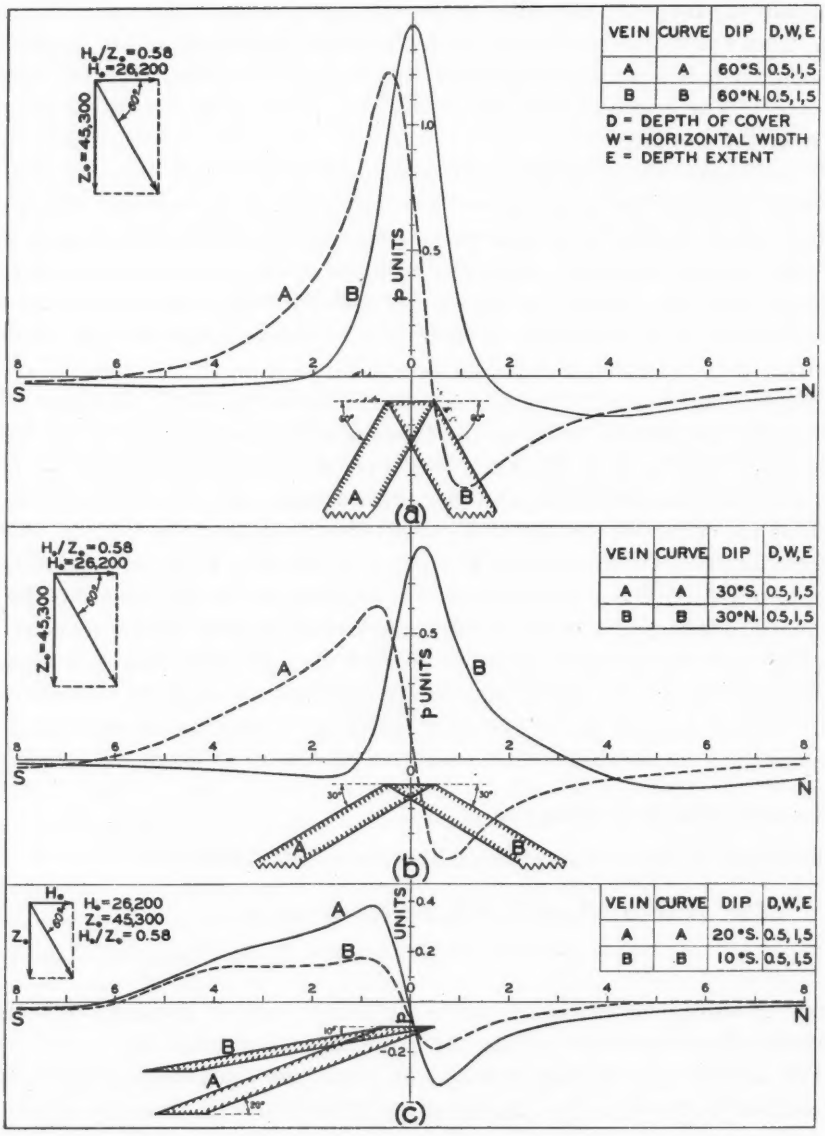

VEIN | CURVE | DIP | D,W,E
A | A | 60°S. | 0.5,1,5
B | B | 60°N. | 0.5,1,5
D = DEPTH OF COVER
W = HORIZONTAL WIDTH
E = DEPTH EXTENT
p UNITS
S
N
(a)
VEIN | CURVE | DIP | D,W,E
A | A | 30°S. | 0.5,1,5
B | B | 30°N. | 0.5,1,5
(b)
VEIN | CURVE | DIP | D,W,E
A | A | 20°S. | 0.5,1,5
B | B | 10°S. | 0.5,1,5
(c)

FIG. 13. Intensity over finite inclined veins striking east. For all veins, depth of cover 0.5, horizontal width 1, depth extent 5, magnetic inclination 60°.

In this case the effect of the lower face manifests itself and, as shown by Curve *B* in Figure 13a, the intensity curve is slightly asymmetrical and both sides of the curve cross the *x*-axis, which is not so in the case for the infinite vein.

For a finite vein which dips north at an angle greater than the angle of magnetic inclination or which dips south at an angle greater than sub-critical dip,

the same general intensity features are observed as for the infinite vein of similar orientation, except that the south flank of the curve crosses the x-axis (Curve A in Fig. 13a).

For a finite vein dipping south at sub-critical dip, a special mathematical case arises. By using the same mathematical relations as used above for the infinite vein, it follows that in this case the intensity over the finite vein becomes

$$\Delta Z = 2kH_o \log_e r_2 r_3 / r_1 r_4. \tag{16}$$

Because of the effect of the lower face in this case, the intensity curve, as shown by Curve A in Figure 13b, lacks the unique characteristics shown by the infinite vein with similar orientation. The positive maximum is larger than the negative maximum, the curve crosses the x-axis at a point lying north of the center of the top face projected vertically to the surface, and the south flank of the curve crosses the x-axis, which is not so in the case for the infinite vein.

It is obvious from equation (16) that, just as in the case of the infinite vein, thin finite veins existing in high magnetic latitudes and dipping at or near sub-critical dip might give no observable vertical magnetic anomaly. At intermediate magnetic latitudes such finite veins might give little or no observable vertical magnetic anomaly. Consequently extreme caution should be used in the interpretation in areas where such veins are suspected.

For a finite vein dipping south at an angle less than sub-critical dip (Curve A in Fig. 13c), the general intensity features are similar to those for sub-critical dip. With decreasing angles of dip, however, there exists an angle such that the negative amplitude is equal to the positive amplitude. This angle depends on the dimensions of the vein. As the angle of dip is decreased further, the negative amplitude exceeds the positive amplitude (Curve B in Fig. 13c). Under such conditions of dip it is conceivable that in plan view on a magnetic map a thin vein of finite length striking in an easterly direction might exhibit a rather pronounced negative center on its up-dip (north) side and, in comparison, a numerically smaller positive center on its down-dip (south) side. For such gentle angles of dip, the south end of the body comes close enough to the surface to distort the south flank of the intensity curve from its customary appearance, so that the curve begins to take on a form similar to that for a horizontal or gently inclined slab of finite depth extent. It is beyond the scope of this paper to consider veins that approximate such slabs. But it is desirable to emphasize the special intensity characteristics of veins dipping at or near sub-critical dip, especially those features near the apices of such veins.

Inclined veins striking neither north nor east

For inclined veins whose strike is nearly meridional, the terms involving $\sin \alpha$ in equation (1) may be neglected, and the above analysis for inclined veins striking magnetic north may be employed. The higher the magnetic latitude, the

greater is the departure from magnetic meridian which may be permitted before these terms must be considered.

For inclined veins whose strike is nearly east, sin $\alpha = 1$ approximately, and the intensity obtained for a similar vein striking exactly east may be used. The higher the magnetic latitude, the greater is the departure from east which may be permitted before the exact value of sin α in equation (1) must be considered.

When the more rigorous analysis is used, the anomaly for an inclined vein of finite depth extent is given by formula (1). For an inclined vein of infinite depth extent formula (1) becomes

$$\Delta Z = 2k \sin\delta\left[(H_o \sin\alpha \sin\delta + Z_o \cos\delta) \log_e r_3/r_1 - (H_o \sin\alpha \cos\delta - Z_o \sin\delta)(\phi_1 - \phi_3)\right]. \tag{17}$$

PRACTICAL USE OF FORMULAS AND THEORETICAL CURVES

The chief usefulness of the formulas and theoretical curves presented in this paper lies in analyzing an observed intensity curve when it is believed that the magnetic body may be tabular in shape. In particular they can give a notion of the possible dimensions and attitude of the tabular magnetic body causing the observed anomaly, provided definite susceptibilities are assumed. Then if the assumed susceptibilities fall within the possible range of the ore bodies being explored, and if the theoretical dimensions of the body and the geologic control suggest that an ore body of economic importance may exist, the anomaly may justify testing.

In a recent publication the writer (1950) has given field examples of the application of theoretical curves of the type presented in this paper.

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THE ELECTROMAGNETIC FIELD DUE TO INDUCED CURRENTS IN A CONDUCTIVE SLAB OF FINITE DIMENSIONS*

A. BELLUIGI†

ABSTRACT

In conformity with what the author (1949a) presented briefly, the theory is developed of the electromagnetic eddy fields relative to a plane, thin, conducting slab with its plane perpendicular to the horizontal ground. The mineral slab is subjected to an alternating inducing magnetic field, paralleling the surface of the ground. After discussing the problem of the finite slab, the special case is considered of a semi-infinite slab (Peters & Bardeen, 1930), e.g., the mineralized vein type, using existing formulas. With adequate development they can be used in the construction of theoretical graphs of the electromagnetic effects of the slab in which eddy currents are produced.

The limiting dimensions, both of the dyke (first case of the finite slab), and the vein (second of the semi-infinite slab case), act noticeably upon the measurable electromagnetic effect, and the influence diagrams characterize the slab-shaped, conducting mineral. Therefore some fundamental characteristics on the surface and at depth of the slab and its extension in depth (thickness) can be deduced.

The present paper consists of two sections, namely, (A) The theory of the finite, plane, and thin slab (dyke) and corresponding general formulas of magnetic influence. (B) A discussion of the special case of the semi-infinite slab, or mineralized vein and of Peters-Bardeen's (1930) integral formulas, and their integration and illustration by means of graphs.

THEORY OF A FINITE SLAB

Assume a plane slab, with rectangular shape ($2L$, $2l$), and minimum thickness, $w \ll 2l \ll 2L$. The co-ordinate system is illustrated in Figure 1. The x axis is

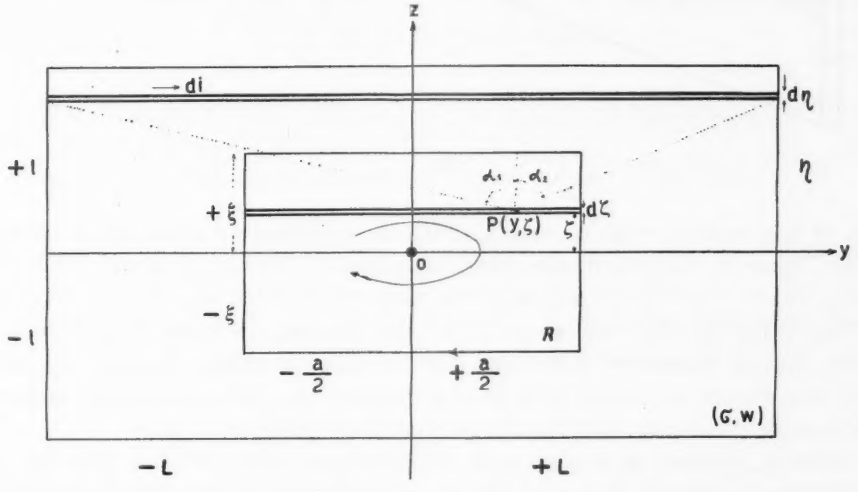

FIG. 1

perpendicular to the paper, zy, at the origin, O. The perpendicular axes y, z are axes of symmetry of the slab; (also the x axis is an axis of symmetry, with its

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trace at O). The horizontal plane of the ground ($z>l$) is parallel to the xy plane.

Consider a primary magnetic field, which is a cosine function of time, acting on this slab-shaped conductor. Of this magnetic field we take only the active portion (i.e. that portion which is apt to produce eddy currents), viz. the component perpendicular to the slab and acting in the direction of the x axis, because $w \ll 2l \ll 2L$. We measure now the secondary (eddy) electromagnetic fields on the surface of the earth in the direction of the x axis, i.e. in the direction perpendicular to the plane of the slab.

If the slab is *finite*, this may indicate a thin mineral inclusion, of the dyke type, dipping with a certain width ($2L$) into the ground ($2l$). If the slab is very extensive ($2L \to \infty$), it denotes a thin mineralized vein, dipping also in the direc-

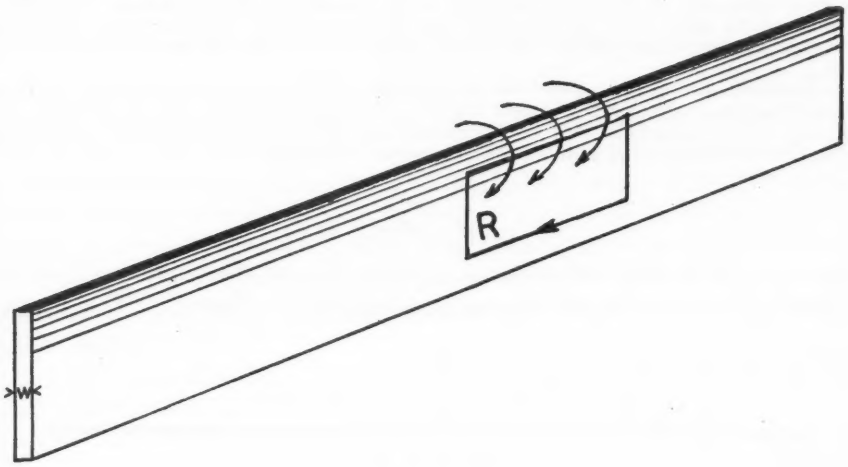

FIG. 2

tion of the vertical with a certain width. Approximately rectangular circuits, R (see Figure 1), with their sides paralleling those of the slab (Foucault currents), are interlinked by the component of the magnetic flux density, $B(t)$, in the slab.

Any imaginary tube of current, "di", in the slab, produces at a point in its plane, $P(y, \zeta)$, interior to a prefixed domain, R, a secondary, or eddy, magnetic field (see Figure 2), which adds to the primary one, $B(t)$; this eddy magnetic field can be measured collectively, or separately (Belluigi, 1949a).

After a number of studies and constructions using suitable devices, this fundamental problem was also solved, namely that of the direct measure of only the eddy electromotive fields. Referring to Figure 1, according to Biot-Savart's law, the magnetic effect of "di" at the point P is

$$H(y, \zeta) = \frac{di}{\eta - \zeta} (\sin \alpha_1 + \sin \alpha_2) \tag{1}$$

where: $\sin \alpha_1 + \sin \alpha_2 = J_1 + J_2 = J$ (see Figure 1), is given by

$$(2) \qquad J = J_1 + J_2 = \frac{L + y}{[(\eta - \zeta)^2 + (L + y)^2]^{1/2}} + \frac{L - y}{[(\eta - \zeta)^2 + (L - y)^2]^{1/2}} \cdot$$

Making allowance for the value di, which is a function of the electromagnetic parameters σ, μ, of the unknown current intensity, $F(\eta)$, (component in the direction of y axis) which varies in the direction of η, we obtain:

$$(3) \qquad H(y, \zeta) = \frac{J \cdot \sigma \cdot \mu \cdot w \cdot F(\eta) d\eta}{\eta - \zeta} \cdot$$

The magnetic flux, induced by the tube of current, "di," into the isle R, is therefore

$$\int_R H(y\zeta) dy d\zeta,$$

and the magnetic flux induced by the whole slab

$$\int_R H(y\zeta) dy d\zeta d\eta,$$

so that the total magnetic field is

$$(4) \qquad \phi = \int_R H(y\zeta) dy d\zeta d\eta + 2a\xi B(t),$$

In this expression in equation (4), Φ, using equation (3), appears as an unknown, and the electrical current $F(\eta)$.

It may be derived immediately from the circuitation theorem:

$$(5) \qquad -\frac{\partial \phi}{\partial t} = 2F(\xi)a$$

Since, $F(\eta) = f(\eta)e^{j\omega t}$; $B(t) = be^{j\omega t}$; $j^2 = -1$; w = radian frequency of the alternating current, by application of equation (4) and performing the operation of equation (5), we obtain

$$(6) \qquad j\omega\mu \int_{-a/2}^{+a/2} dy \int_{-\xi}^{+\xi} d\zeta \int_{-l}^{+l} \frac{\sigma w J}{\eta - \zeta} f(\eta) d\eta = -2af(\xi) + 2aj\omega\xi b,$$

"integral equation of the second kind," which may be transformed as follows:

$$(7) \qquad j\omega\sigma w\mu \int_{-l}^{+l} \Omega(\xi, \eta) f(\eta) d\eta = -2af(\xi) + 2aj\omega\xi b,$$

where the kernel $\Omega(\xi, \eta)$ is given by,

$$\Omega(\xi, \eta) = \int_{-\xi}^{+\xi} \frac{d\zeta}{\eta - \zeta} \int_{-a/2}^{+a/2} (J_1 + J_2) dy. \tag{8}$$

Since,

$$\int_{-a/2}^{+a/2} J_1 dy = \int \left\{ (L + y)^2 + (\eta - \zeta)^2 \right\}^{1/2} \Big]_{-a/2}^{+a/2}$$

$$\int_{-\xi}^{+\xi} \frac{d\zeta}{\eta - \zeta} \int_{-a/2}^{+a/2} J_1 dy = A + B,$$

where,

$$A = \int_{-\xi}^{+\xi} \frac{\left[(L + a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}{\eta - \zeta} d\zeta$$

$$B = -\int_{-\xi}^{+\xi} \frac{\left[(L - a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}{\eta - \zeta} d\zeta \tag{9}$$

and the analogous expression for:

$$\int_{-\xi}^{+\xi} \frac{d\zeta}{\eta - \zeta} \int_{-a/2}^{+a/2} J_2 dy$$

by integrating we have:

$$\Omega(\xi, \eta) = \left[\sum_{1}^{n=3} f_n(\zeta\eta) - \sum_{4}^{n=5} f_n(\zeta\eta) \right]_{\zeta=-\xi}^{\zeta=+\xi} \tag{10}$$

where

$$f_1(\zeta\eta) = (\eta - \zeta) + \left[\left(L - \frac{a}{2} \right)^2 + (\eta - \zeta)^2 \right]^{1/2}$$

$$f_2(\zeta\eta) = (L - a/2) \ln \frac{(\eta - \zeta) - (L - a/2) + \left[(L - a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}{(\eta - \zeta) + (L - a/2) + \left[(L - a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}$$

$$f_3(\zeta\eta) = \frac{(L - a/2)^2}{(\eta - \zeta) + \left[(L - a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}} \tag{11}$$

$$f_4(\zeta\eta) = (\eta - \zeta) + \left[\left(L + \frac{a}{2} \right)^2 + (\eta - \zeta)^2 \right]^{1/2}$$

$$f_5(\zeta\eta) = (L + a/2) \ln \frac{(\eta - \zeta) - (L + a/2) + \left[(L + a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}{(\eta - \zeta) + (L + a/2) + \left[(L + a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}$$

$$f_6(\zeta\eta) = \frac{(L + a/2)^2}{(\eta - \zeta) + \left[(L + a/2)^2 + (\eta - \zeta)^2 \right]^{1/2}}.$$

Equation (6) becomes eventually

$$j\omega\sigma\mu w \int_{-l}^{+l} \left[\sum_{1}^{3} f_n(\zeta\eta) - \sum_{4}^{5} f_n(\zeta\eta) \right]_{-\xi}^{+\xi} f(\eta)d\eta = -2af(\xi) + 2aj\omega\xi b.$$

The integral equation (7), or the above expression may be simplified, and *remains formally the same*, if we consider: $\sin\alpha_1+\sin\alpha_2=2$, i.e., a slab of infinite length in the direction of y.

This case has been studied in its basic aspects (Belluigi, 1946) and will be developed further at this point.

In the following section we shall derive the Peters-Bardeen's (1930) integral resolving formulas (Belluigi, 1946), and shall integrate the consequent expression of the secondary magnetic field, B_s.

THEORY OF A SEMI-INFINITE SLAB

By substituting: $\sin\alpha_1+\sin\alpha_2=2$ in equation (3), the magnetic flux, induced by "di" in P, in the small strip "$d\zeta$" of the rectangular circuit $[-\xi, +\xi]$ will be expressed by

$$2a\sigma\mu wF(\eta)d\eta \int_{-\xi}^{+\xi} \frac{d\zeta}{\eta - \zeta} = a\sigma\mu wF(\eta)d\eta \lg \left(\frac{\eta + \xi}{\eta - \xi}\right)^2. \tag{12}$$

Adding the magnetic flux, induced by the entire vein of infinite extent in the direction of y, to the primary magnetic flux, $B_i(l)$ yields as in equation (4)

$$\phi = 2a\cdot z\cdot\beta(l) + 2a\sigma w\mu\cdot \int_0^l \lg \left(\frac{\eta + \xi}{\eta - \xi}\right)^2 F(\eta)d\eta. \tag{13}$$

Since the rate of change of the magnetic flux across the area of rectangle R equals the integral of $F(\eta)$ along the closed circuit (see equation [5]), differentiating Φ with respect to time and keeping in mind the signs, we obtain again the simplified integral equation of the second kind, already mentioned (Belluigi, 1946). This equation using the symbols and units of equation (2), $(\eta=z, \xi=\beta)$, may be written

$$(f(z) = -j\omega bz -) j\omega\mu\sigma w/2\pi) \int_0^l \lg \left(\frac{z + \beta}{z - \beta}\right) f(\beta)d\beta \tag{14}$$

or

$$f(z) = cz + \frac{\lambda}{l} \int_0^l \lg \left(\frac{z + \beta}{z - \beta}\right) f(\beta)d\beta \tag{15}$$

Peters-Bardeen's (1930) formula, with

$$c = -j\omega b, \qquad \lambda = -j\frac{wl}{\pi s^2}, \qquad s = (\pi f\mu\sigma)^{-1/2} \tag{16}$$

an integral equation of the second kind, solved in (Belluigi, 1946) (see equation 19), by the Liouville-Neumann method for λ sufficiently small. This method holds also for the general integral equation of the finite slab, in equation (7), or its subsequent counterpart.

Having thus deduced, by solving the integral equation, the fundamental unknown, $f(z)$, the computation of the components of magnetic flux density, B_s, in the slab is possible. We apply Biot-Savart's law (the magnetic flux density being zero in the direction of y and active in the direction of the other two axes).

A segment of thickness "du" (of the slab) produces at any point in the space $M(x, z)$, at a distance r from "du," and making an angle $xr = \alpha$, an electromotive field,

$$dB_{sz} = \frac{f(u)du \cdot \sin \alpha}{r} \tag{17}$$

with a multiplier

$$-\frac{\lambda b e^{j\omega t}}{lc} = \frac{w}{\omega \pi s^2}(\cos \omega t + j \sin \omega t) \tag{18}$$

so that B_{sx} will be the real part of the integral, whose integrand function is $(z-u)f(u)du/r^2$. Similarly B_{sz} will be the real part of the integral, whose integrand function is: $xf(u)du/r^2$.

Before we make these computations, it is necessary to examine analytically the function $f(u)$, see equation (19), and to integrate the useful terms of equation (19), which is the solution of the integral equation (15) obtained by the method of successive substitutions:

$$f(u) = c\left[u + \frac{\lambda}{l}\int_0^l \lg \frac{u+\beta}{u-\beta} \cdot \beta d\beta + \frac{\lambda^2}{l^2}\int_0^l \lg \frac{u+\alpha}{u-\alpha}\int_0^l \lg \frac{\alpha+\beta}{\alpha-\beta}\beta d\beta d\alpha + \cdots\right] \tag{19}$$

where u varies in interval $(-l, +l)$, and the integration variables in interval $(0, l)$.

We observe now that the terms:

$$\lg \frac{\alpha+\beta}{\alpha-\beta}, \qquad \lg \frac{u+\beta}{u-\beta}, \qquad \lg \frac{u+\alpha}{u-\alpha},$$

which appear in the integrand functions of $f(u)$, (i.e. substantially hyperbolic functions, $2 \tanh^{-1} \beta/\alpha$), cross along their paths of integration, points that are situated at the frontier of the field of holomorphy of the functions themselves.

The contour-integrals of such analytic functions are therefore improper integrals, although convergent ones, and in their expansion contain evidently

complex terms. It should be noted that the expression $\lg(\alpha+\beta/\alpha-\beta)$ is the holomorphic function which may assume complex values for real values of the independent variable, β.

It happens often that we move along portions of the frontier of the holomorphy field of the above-said analytic functions. Therefore, we may foresee a probable multiformity also for the real parts of the B_{sx}'s and B_{sz}'s. In other words, the question is: along the frontier, represented by the negative semi-axis, of the field of holomorphy of $\lg \Delta$, which branch of this function must be chosen in order to compute its limit when P approaches Q?

We shall examine the case of the main Napierian logarithm of Δ, for which $-\pi \leqq \arg \Delta \leqq \pi$ holds, choosing

$$\begin{aligned} \lg \Delta &= \lg |\Delta| + j\cdot\pi; \qquad (\Delta < 0), \\ \lg \Delta &= \lg |\Delta| + j\cdot 0; \qquad (\Delta > 0). \end{aligned} \tag{20}$$

We do so in order to avoid the likely multiformity of the real parts of the B_{sx}'s and B_{sz}'s, when we use the general expression:

$$\begin{aligned} \lg \Delta &= \lg |\Delta| + j\pi + 2jk\pi; \qquad (\Delta < 0), \\ \lg \Delta &= \lg |\Delta| + j2k\pi; \qquad (\Delta > 0), \end{aligned} \tag{21}$$

where k is any integer, positive, negative, or zero.

After these statements let us note that the last integral of the $f(u)$ cannot be expressed by a finite number of terms by means of the known elementary transcendental functions, and that a last term, constituted by a series, must appear in the expression of $f(\Delta)$.

As a matter of fact, we obtain for $f(u)$:

$$\begin{aligned} f(u) = {} & cu + \frac{c\lambda}{l}(1+\lambda)\left[l\cdot u + (l^2-u^2)\operatorname{ctnh}^{-1}\frac{u}{l}\right] \\ & \mp c\frac{\pi^2\lambda^2}{6l^2}(l-u)^2\cdot(2l+u) + j\left[\frac{c\pi\lambda^2}{6l^2}\left\{(3l^2-u^2)u\lg\frac{u^2}{l^2-u^2}\right.\right. \\ & \left.\left. - 4l^3\operatorname{ctnh}^{-1}\frac{u}{l} + l[lu + 3(l^2-u^2)]\right\} \mp \frac{c\pi\lambda}{2l}(l^2-u^2)\right] \\ & + c\frac{\lambda^2}{l^2}\int_0^l (l^2-\alpha^2)\operatorname{ctnh}^{-1}\frac{\alpha}{l}\lg\left(\frac{u+\alpha}{u-\alpha}\right)d\alpha, \end{aligned} \tag{22}$$

if it holds $0<u<l$ or: $-l<u<0$.

It is evident that equation (22) (except for the last integral, which cannot be expressed by elementary transcendental functions, but only by a power expansion), is not suitable for the computation of B_{sx} and B_{sz} by means of further integrations, see equation (28).

We must therefore confine ourselves to the first approximation for $f(u)$,

neglecting the integral term with the coefficient λ^2/l^2. This assumption is quite justified when λ is sufficiently small. Hence equation (22) is simplified and $f(u)$ becomes

$$(23) \qquad f(u) = cu + \frac{c\lambda}{l}\left[lu + (l^2 - u^2)\ \mathrm{ctnh}^{-1} - \frac{u}{l} \mp j - \frac{\pi}{2}(l^2 - u^2)\right]$$

for: $0<u<l$; $-l<u<0$.

Introducing the expression of $f(u)$ given by equation (23) into equation (17), and then equation (28) (by means of integrals that can be expressed by elementary transcendental functions), we may derive the magnetic flux densities, B_s, through suitable expansions in series, that we shall see at once.

Using equation (16), in relation with equation (19) becomes in this case

$$(24) \qquad f(u) = -j\omega b\left[u - \frac{jw}{\pi s^2}\int_0^l \lg\frac{u+\beta}{u-\beta}\beta d\beta\right]$$

for:

$$(25) \qquad \begin{cases} -l < u < l \\ 0 < \beta < l \end{cases}$$

and equation (23) may be written:

$$(26) \qquad \begin{aligned} f(u) = &-\omega b\left[\frac{w}{\pi s^2}\left\{lu + (l^2 - u^2)\ \mathrm{sett.\ tgh}\frac{u}{l}\right\}\right] \\ &+ j\left[u + \frac{w}{\pi s^2}\cdot\frac{\pi}{2}(l^2 - u^2)\right] \qquad \text{for } -l < u < 0 \end{aligned}$$

$$(27) \qquad \begin{aligned} f(u) = &-\omega b\left[\frac{w}{\pi s^2}\left\{lu + (l^2 - u^2)\ \mathrm{sett.\ tgh}\frac{u}{l}\right]\right\} \\ &+ j\left[u - \frac{w}{rs^2}\cdot\frac{\pi}{2}(l^2 - u^2)\right] \qquad \text{for } 0 < u < l. \end{aligned}$$

The components of B_s, in equation (17) may be written thus:

$$(28) \qquad \left|\begin{aligned} B_{sx} &= Re\left[\frac{-\lambda b e^{j\omega t}}{lc}\int_{-l}^{+l}\frac{z-u}{x^2+(z-u)^2}f(u)du\right] \\ B_{sz} &= Re\left[\frac{\lambda b e^{j\omega t}}{lc}\int_{-l}^{+l}\frac{\delta}{x^2+(z-u)^2}f(u)du\right]. \end{aligned}\right.$$

Substituting equations (18), (26), (27) in these expressions and denoting

by $f(\bar{u})$ the value of $f(u)$ for: $-l<u<0$, and by $f(u)$ the value of $f(u)$ for: $0<u<l$, we obtain:

$$B_{sx} = \frac{wb}{\pi^2 s^4}(\pi s^2 \sin \omega t - wl \cos \omega t) \int_{-l}^{+l} \frac{(u-z)u\,du}{x^2+(z-u)^2}$$

$$+ \frac{w^2 b}{2\pi s^4} \sin \omega t \left[\int_0^{l} \frac{(z-u)(l^2-u^2)\,du}{x^2+(z-u)^2} - \int_{-l}^{0} \frac{(z-u)(l^2-u^2)\,du}{x^2+(z-u)^2} \right]$$

$$+ \frac{w^2 b}{\pi^2 s^4} \cos \omega t \int_{-l}^{+l} \frac{(z-u)(l^2-u^2)}{x^2+(z-u)^2} \operatorname{sett.\,tgh} \frac{u}{l}\,du$$

$$(30) \quad \operatorname{ctnh}^{-1} \frac{u}{l} = \sum_{n=0}^{\infty} \frac{1}{2n+1} \cdot \frac{1}{l^{2n+1}} \cdot u^{2n+1} = \frac{u}{l} + \frac{1}{3}\frac{u^3}{l^3} + \frac{1}{5}\frac{u^5}{l^5} + \cdots .$$

$$-l < u < l.$$

If the preceding expansion is limited to the first term we obtain the value of the horizontal component in the direction of the x axis, of the eddy magnetic flux density, with a finite number of terms (with inverse tangents and logarithms).

$$B_{sx} = \frac{wb}{\pi^2 s^4} \{\pi s^2 \sin \omega t - wl \cos \omega t\}$$

$$\cdot \left[2l - x\left(\tan^{-1} \frac{l-z}{x} + \tan^{-1} \frac{l+z}{x} \right) + z \lg \left(\frac{x^2+(l-z)^2}{x^2+(l+z)^2} \right)^{1/2} \right]$$

$$+ \frac{w^2 b}{2\pi s^4} \left\{ \left[z^2 - (l^2+x^2) \lg \frac{\{[x^2+(l-z)^2][x^2+(l+z)^2]\}^{1/2}}{x^2+z^2} \right.\right.$$

$$\left.\left. + l^2 - 2zx \left[2 \tan^{-1} \frac{z}{x} + \tan^{-1} \frac{l-z}{x} - \tan^{-1} \frac{l+z}{x} \right] \right\} \sin \omega t \right.$$

$$+ \frac{w^2 b}{\pi^2 s^4} \left\{ 2\left[\frac{l^2}{3} + z^2 - l^2 - x^2 \right] \right.$$

$$+ \frac{z}{l}(z^2 - l^2 - 3x^2) \lg \left[\frac{x^2+(l-z)^2}{x^2+(l+z)^2} \right]^{1/2}$$

$$(31) \qquad \left. + \frac{x}{l}(l^2 + x^2 - 3z^2) \left(\tan^{-1} \frac{l-z}{x} + \tan^{-1} \frac{l+z}{x} + \cdots \right) \right\} \cos \omega t.$$

Similarly we find for the vertical component in the direction of the x axis, of the eddy magnetic flux density, B_{sz}

$$
\begin{aligned}
B_{sz} = {} & \frac{wbx}{\pi^2 s^4}\,[\pi s^2 \sin \omega t - wl \cos \omega t] \\
& \cdot \left\{ \lg \left(\frac{x^2 + (l-z)^2}{x^2 + (l+z)^2} \right)^{1/2} + \frac{z}{x} \left(\tan^{-1} \frac{l-z}{x} + \tan^{-1} \frac{l+z}{x} \right) \right\} \\
& + \frac{w^2 bx}{2\pi s^4} \sin \omega t \left[z \lg \frac{(x^2+z^2)^2}{[x^2+(l+z)^2][x^2+(l-z)^2]} \right. \\
& \left. + \frac{l^2 + x^2 - z^2}{x} \left\{ \tan^{-1} \frac{l-z}{x} + \tan^{-1} \frac{l+z}{x} + 2 \tan^{-1} \frac{z}{x} \right\} \right] \\
& + \frac{w^2 bx}{\pi^2 s^4} \cos \omega t \left[-4z + \frac{1}{l} (l^2 + x^2 - 3z^2) \lg \left(\frac{x^2 + (l-z)^2}{x^2 + (l+z)^2} \right)^{1/2} \right. \\
& \left. + \frac{z}{lx} (l^2 - z^2 + 3x^2) \left(\tan^{-1} \frac{l-z}{x} + \tan^{-1} \frac{l+z}{x} \right) \right] + \cdots .
\end{aligned}
\tag{32}
$$

These expressions reduce to the usual form

$$B_{sx} = M \sin \omega t + N \cos \omega t, \tag{33}$$

$$B_{sz} = P \sin \omega t + Q \cos \omega t, \tag{34}$$

with:

$$
\begin{aligned}
M &= \phi_1(c, c', h, k, \beta, \beta', \alpha, \alpha', \Delta_1), \\
P &= \phi_1'(c, c', h, k, \beta, \beta', \alpha, \alpha', \Delta_1), \\
N &= \phi_2(c'', h, k, \beta, \alpha, \Delta_2, \Delta_3), \\
Q &= \phi_2'(c'', h, k, \beta, \alpha, \Delta_2, \Delta_3),
\end{aligned}
\tag{35}
$$

where:

$$
\begin{aligned}
& c = \frac{wb}{\pi s^2} l, \qquad c' = \frac{w^2 b}{2\pi s^4} l^2, \qquad c'' = \frac{w^2 b}{\pi^2 s^4}, \\
& h = \frac{x}{l}, \qquad k = \frac{z}{l}, \\
& \Delta_1 = k^2 - 1 - h^2, \qquad \Delta_2 = k^2 - 2 - 3h^2, \qquad \Delta_3 = h^2 + 2 - 3k^2 \\
& \alpha = \tan^{-1} 2h/(h^2 + k^2 - 1) \qquad \alpha' = \tan^{-1} 2hk/[(h^2 + k^2)^2 + (h^2 - k^2)] \\
& \beta = \lg \{ [h^2 + (k+1)^2]/[h^2 + (k-1)^2] \} \\
& \beta' = \lg \{ (h^2 + k^2)^2/[h^2 + (k+1)^2][h^2 + (k-1)^2] \}
\end{aligned}
\tag{36}
$$

namely:

$$M = (2c + c') - c\left[h\alpha + k/2\cdot\beta\right] - c'\left[2hk\alpha' + \frac{\Delta_1}{2}\beta'\right]$$

(37)

$$= (2c + c') - c\left[h\alpha + \frac{k\beta}{2}\right], \qquad (w \to 0),$$

(38) $$P = c\left[k\alpha - \frac{h\beta}{2}\right] + c'\left[\Delta_1\alpha' - h\beta' k\right]$$

(39) $$Q = c''l^2\left[4hk + \Delta_2\alpha + h\Delta_3\frac{1}{2}\beta\right]$$

(40) $$N = c''l^2\left[2\left\{k^2 - h^2 - 5/3\right\} + h\alpha\Delta_3 - \frac{\beta}{2}\Delta_2\right]$$

The graphical transcription of the coefficients N, Q, M, P, in phase and out of phase by 90° with respect to $B_i(t)$, presents no difficulty. On the contrary it is easier, as shown for M in equation (36), because the terms of their analytical expressions can be further reduced, provided that the thickness of the slab is sufficiently small.

The graphs of the coefficients, of which we present some characteristic examples have been calculated for different vertical thicknesses, l, of the slab ($l=1$; 3; 5; 7; 10), and various depths ($K=2$; 3; 5; 7; 10). (See Figure 3.)

On the abscissae are always plotted the h (on logarithmic scale), for $h=x/l$ ranging from 0, 1 to 10), and the ordinates represent the values of the coefficients of B_s (on linear scale), N, Q, of the components of B_{sz}, B_{sz} in phase with B_i. The values of these coefficients have been calculated for $b=1$, $w=l/10$. s has been calculated for 500 cycles, resistivity 10 ohm-cm, and multiplied by 10^9: l has always been chosen such that w is smaller than the critical thickness, s.

Apart from the signs and absolute values, M and P present profiles similar respectively to the profiles of N and Q. By examining the behavior of coefficient N (of the component B_{sz} in phase with the inducing $B_i(t)$), we observe (see Figure 3), that N decreases as h increases (for a given l), i.e., in proportion to the distance of the mineral slab, for any value of l; or, for x constant, N decreases as l decreases. N decreases also for increasing values of K, i.e., when the depth of the slab increases. Furthermore, N decreases as l decreases for a given z.

For an assumed value of K, the effect, B_s, on the contrary, increases as the vertical width, l, increases; however its profile retains the same shape, $B_s(h)$.

The behavior of the above-mentioned coefficients is thus far, similar to analogous coefficients of secondary electromagnetic effects of buried conducting bodies, for different extents, depths and inductor types. However, their main feature is the existence of minima, $B_s(h)$, and reversal of signs, (Figure 3). The

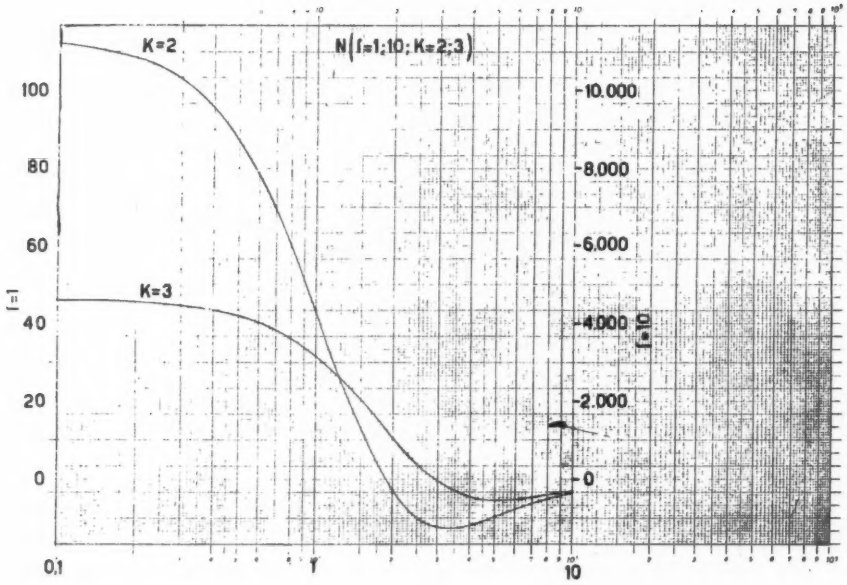
N(f=1;10; K=2;3)
K=2
K=3
100
80
60
40
20
0
f=1
10.000
8.000
6.000
4.000
2.000
0
f=10
0,1
1
10

FIG. 3

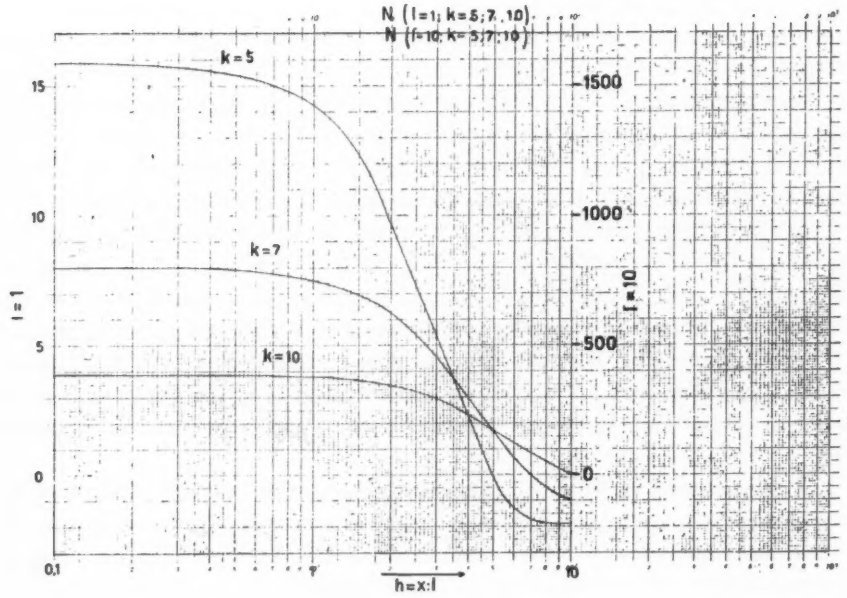
N (f=1; k=5;7;10)
N (f=10; k=5;7;10)
k=5
k=7
k=10
15
10
5
0
f=1
1500
1000
500
0
f=10
0,1
1
10
h=x:f

FIG. 4

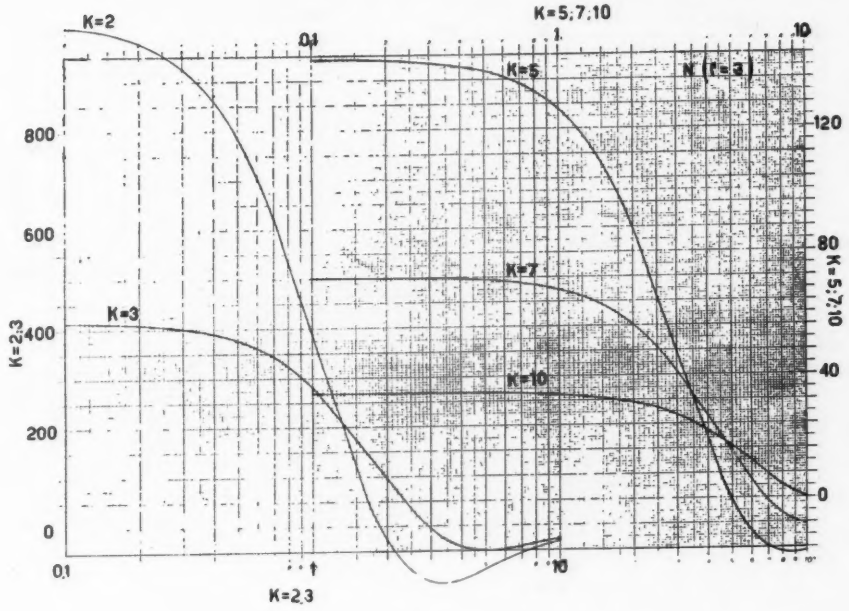
K=2
K=5;7;10
K=5
K=7
K=3
K=10
N (t=3)
K=2;3
K=5;7;10
0.1
1
10
800
600
400
200
0
120
80
40
0
K=2;3

FIG. 5

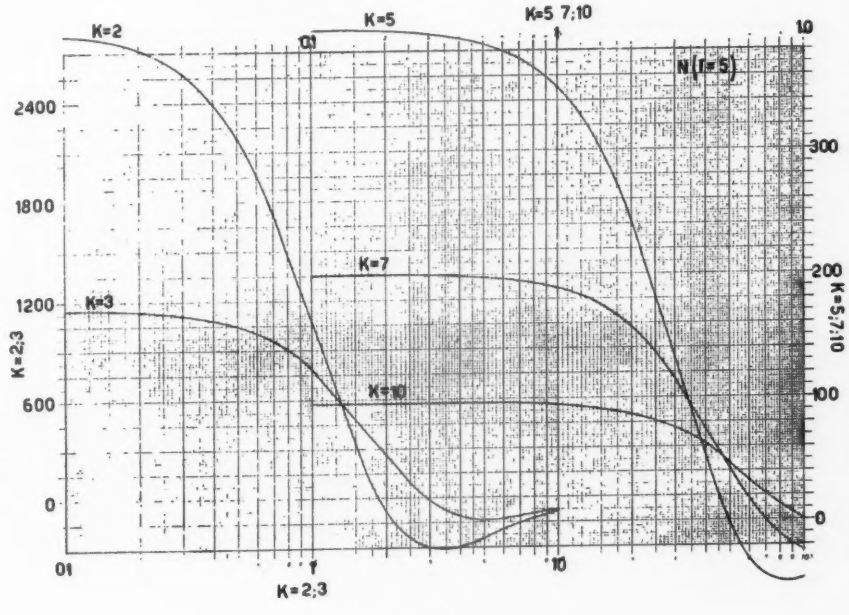
K=2
K=5
K=5 7;10
N (t=5)
K=7
K=3
K=10
K=2;3
K=5;7;10
0.1
1
10
2400
1800
1200
600
0
300
200
100
0
K=2;3

FIG. 6

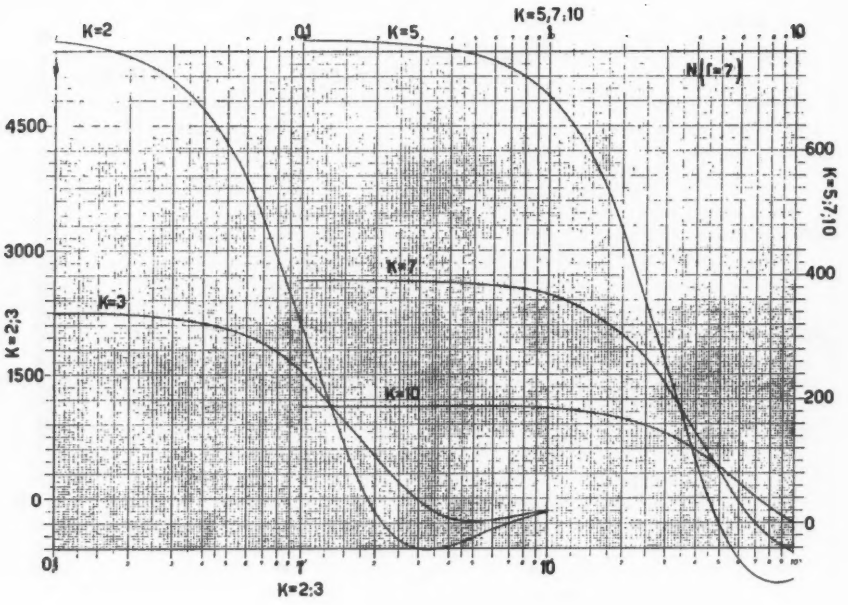
K=2
K=5,
K=5,7,10
N (r=7)
4500
3000
1500
0
K=2;3
600
400
200
0
K=5;7;10
K=7
K=3
K=10
0,1
1
10
K=2;3

FIG. 7

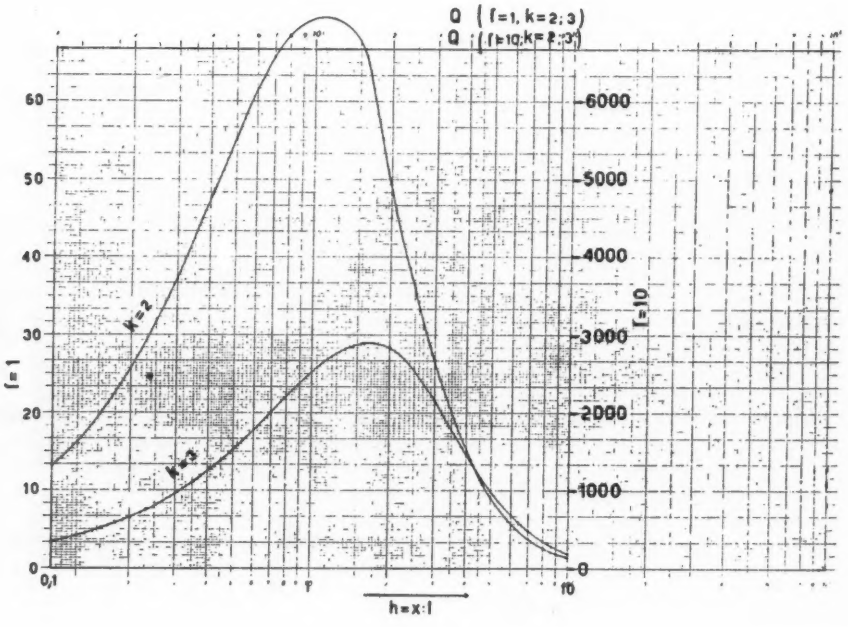
Q (r=1, k=2;3)
Q (r=10;k=2;3)
60
50
40
30
20
10
0
r=1
K=2
K=3
6000
5000
4000
3000
2000
1000
0
r=10
0,1
1
10
h=x:l

FIG. 8

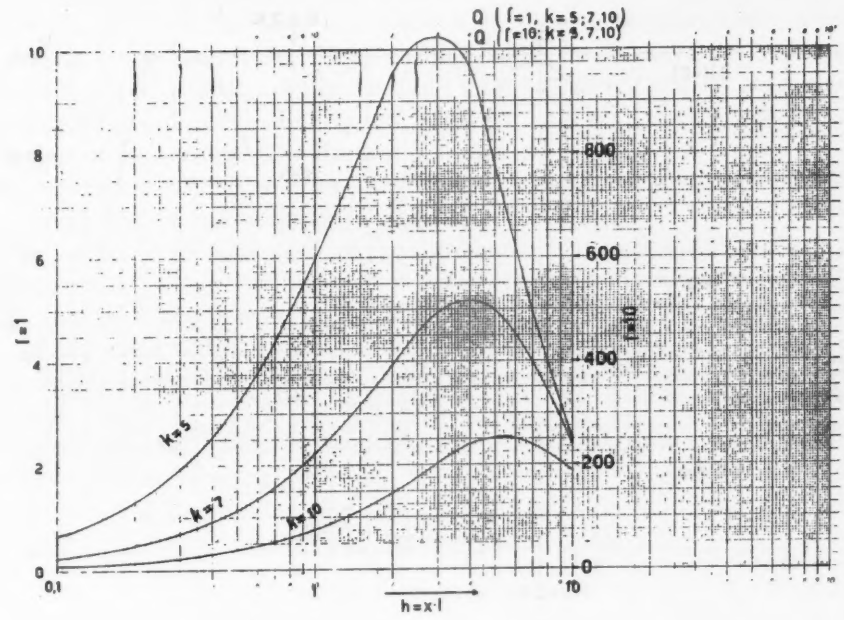
Q (f=1, k=5;7;10)
Q (f=10; k=5,7,10)
800
600
400
200
0
f=1
f=10
k=5
k=7
k=10
0,1
1
10
h=x·l

FIG. 9

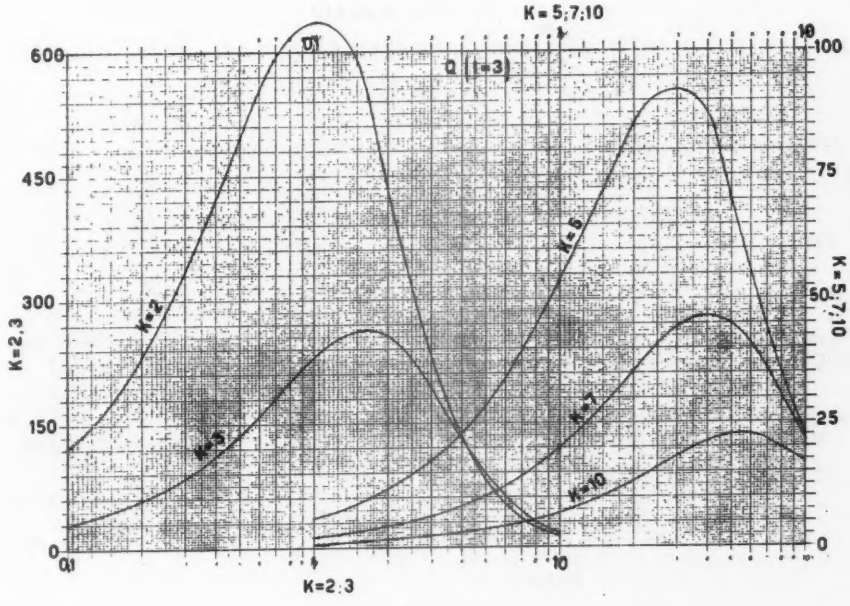
K=5;7;10
Q (f=3)
600
450
300
150
0
K=2,3
100
75
50
25
0
K=5,7,10
k=2
k=5
k=5
k=7
k=10
0,1
1
10
K=2,3

FIG. 1c

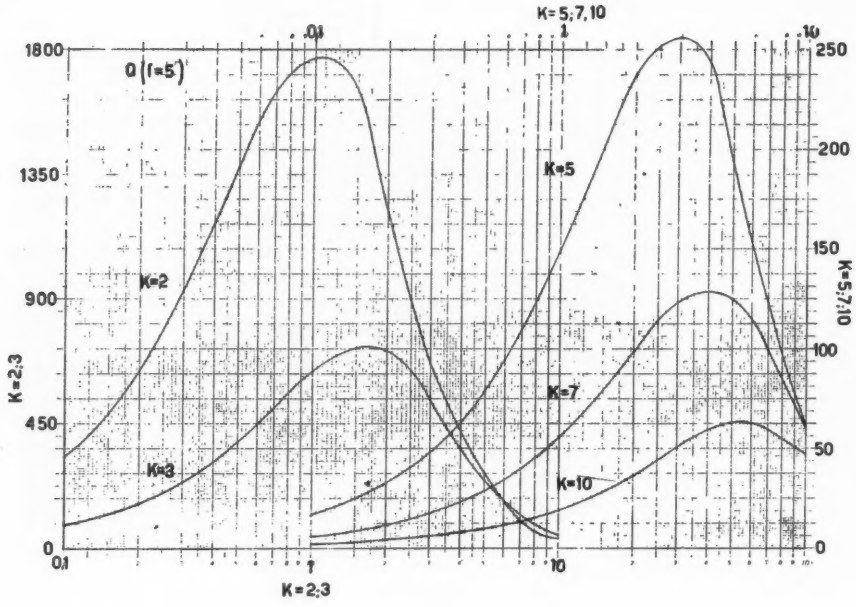
K=5;7,10
0,1
1
10
1800
1350
900
450
0
Q (r=5)
K=2
K=3
K=5
K=7
K=10
250
200
150
100
50
0
K=2;3
K=5;7;10
0,1
1
10
K=2;3

FIG. 11

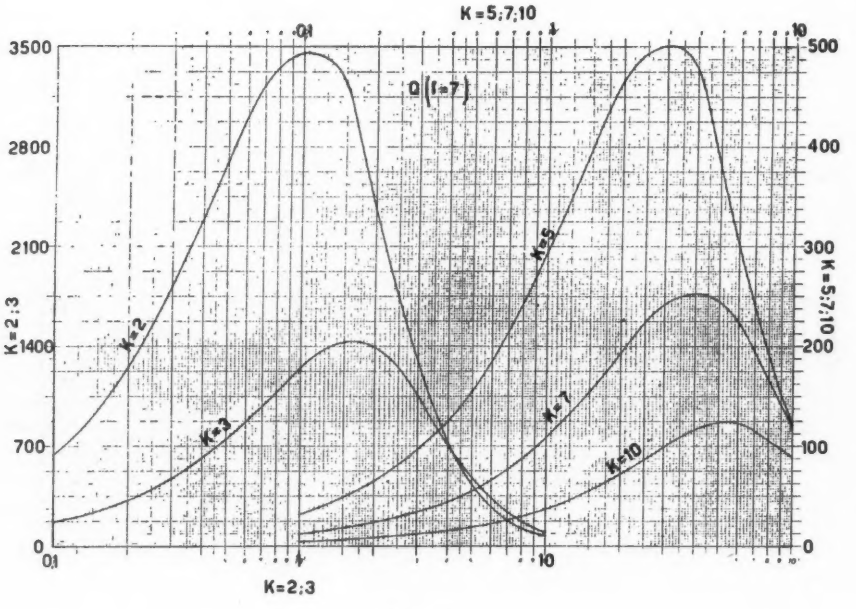
K=5;7;10
0,1
1
10
3500
2800
2100
1400
700
0
Q (r=7)
K=2
K=3
K=5
K=7
K=10
500
400
300
200
100
0
K=2;3
K=5;7;10
0,1
1
10
K=2;3

FIG. 12

greater the depth of the slab, i.e., when K increases, the more these minima flatten and move away from the disturbing body, for fixed values of l.

Figures 3 and 4 illustrate this fact and refer to cases: $L=1$; $l=10$; $K=2$; 3; 5; 7; 10. Other intermediate cases of l, ($l=3$; 5; 7; $K=2$; 3; 5; 7; 10), confirm further the influence law. (See Figures 5, 6, and 7.)

It may be convenient to draw the diagrams of N (for instance, $l=1$; $K=2$), on a double logarithmic scale, as in Figure 8.

The profiles of coefficients Q (of the component, B_{sz}, in phase with $B(t)$), present maximum values that, when K is small, permit the determination of the vertical width, l, of the slab: $l=x_{max}$, while large values of K furnish the upper limit of the same width: $l<x_{max}$. For a given K, the values of Q increase as l increases, although they maintain their profile pattern, as pointed out in the case of N.

The Q curves do not appear symmetrical with respect to the ordinates of the maximum values, but they decrease more rapidly at the farther end of the mineral vein. Figure 10 illustrates the trend of the Q curve for $K=5$; 7; 10, in two cases: $l=1$; $l=10$. Figures 10, 11 and 12 refer to cases

$$l = 3; \quad K = 2; 3; 5; 7; 10$$
$$l = 5; \quad K = 2; 3; 5; 7; 10$$
$$l = 7; \quad K = 2; 3; 5; 7; 10.$$

CONCLUSIONS

The study of the eddy magnetic fields in a plane, vertical, thin slab (extensive vein), may be in conclusion considered terminated, with solutions sufficiently approximated and useful for the interpretation of electro-magnetic field profiles. These results may prove useful when prospecting in mine galleries, rather than in surface prospecting, both for driving exploratory drift, and for the lateral exploration of gallery pillars, that may also contain valuable ore.

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SOME RESULTS OF GEOPHYSICAL PROSPECTING CONDUCTED FOR THE GEOLOGICAL SURVEY OF INDIA FROM 1945–1948*

G. DESSAU†

ABSTRACT

The methods used and some results obtained from geophysical investigations conducted by the Geophysical Section of the Geological Survey of India from 1945–1948 are presented. The many difficulties encountered in obtaining the proper instruments necessitated the widespread use of equipment made by the Section. This is one of the reasons why electrical resistivity and spontaneous polarization methods were employed in preference to others. The majority of the geophysical surveys during this three year period were concentrated in the search for minerals, water supplies, and in the solution of foundation engineering problems. The emphasis on these phases of geophysical prospecting rather than on oil surveys was necessary because, of the types of equipment available, as well as the priority assigned to these projects. Two spontaneous polarization, two magnetic, and two resistivity surveys are described, in addition to one carried out jointly by electrical and seismic methods. The geological background of these investigations are also briefly mentioned together with some details of the equipment used.

INTRODUCTION

The Geophysical Section of the Geological Survey of India was initiated in July 1945 with the appointment of the author. Instruments were almost nonexistent and because of the conditions existing at that time, were manufactured locally. The all Indian staff had no previous knowledge or experience of geophysical prospecting and had to be trained. Two more European specialists were subsequently appointed. There were also other difficulties which elsewhere are not easily imagined, for example, one piece of motor transport for each geophysical party in the field remained a goal which never was achieved.

More details on these points may be found in other papers by the writer (1948a, b). However it is not intended to be plaintive or apologetic, but rather to relate what may be of more general interest about the work of a young organization which, although starting from scratch as far as equipment and personnel were concerned, was still able to deliver useful results. The final interpretation of the field data has not been completed because some of the investigations which will be referred to and some which are part of a very long-range program, are still underway.

MAGNETIC SURVEYS

The Geophysical Section had at its disposal one Askania-Schmidt vertical intensity magnetometer, and for a short period, two more instruments (Watts)

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of a similar type loaned by the Survey of India. A Thalèn-Tiberg magnetometer (Berg), which was obtained later on, proved to be defective in its construction. Therefore, the measurement of horizontal intensity anomalies, which is no less important in low latitudes than the measurement of the vertical anomalies, had to be made with makeshift equipment of relatively low accuracy. The recording of daily variations was out of the question, therefore limiting the choice of possible investigations.

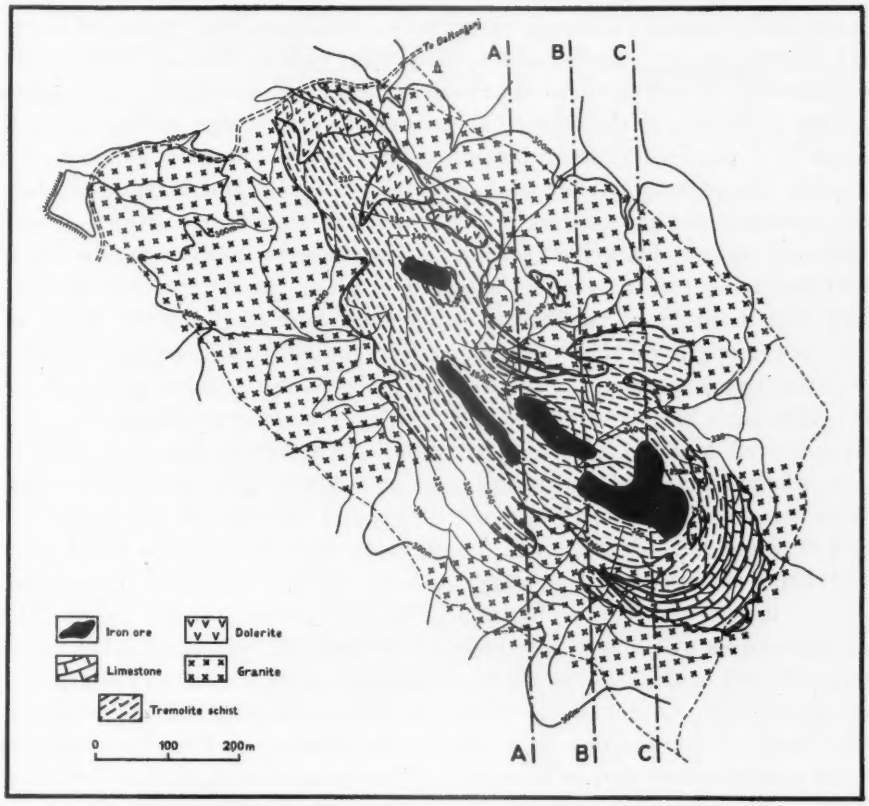

FIG. 1. Schematic Geological Map of Gore Iron Ore Deposit (Daltonganj, Bihar).

The Iron Ore Deposits of Gore near Daltonganj (Bihar Province)

A few patches of iron ore composed of magnetite and hematite in approximately equal parts appear toward the top of a small elongated hill near Gore. Sen Gupta and Sen Gupta (1939) postulated that these patches represent the outcrop of a seam- or vein-like, sharply dipping ore body of considerable vertical extent forming the core of the hill. But Auden of the Geological Survey of India (unpublished report of 1940 which evidently is the source of Dunn's (1941) brief mention) described evidence to the effect that the upper part of the hill cor-

responds to a synclinal structure composed of Archaean metamorphic rocks, whose axis is coincident with the topographical axis of the hill itself. The sequence of the metamorphic rocks, from bottom to top, is crystalline limestone, tremolite schist and iron ore. The small, schematic and simplified geological map (Fig. 1), based on Auden's surveys and surveys of the geophysical party, shows the surface relationships of the various rocks.

The hill was covered with a grid of stations placed every 20 meters along parallel transverse profiles, which were in turn spaced 30 meters apart. In less than one-half a square kilometer, the vertical component was measured at more than 1,400 stations and the horizontal component at 800, whereas the declination was determined at 170 stations. When the results were plotted, the maps showed a number of erratically distributed anomalies of varying sign having intensities as large as a hundred thousand gammas and more. The arrangement of the anomalies was therefore taken as completely irregular and attributed mainly to the influence of the boulders of ore which are abundantly strewn over the ground and have a marked effect on an instrument standing nearby. A few measurements on tree tops up to a height of about 12 meters were also tried hoping that it would be possible to apply the formulas giving the depth of a deposit as a function of values obtained at different levels. But the determinations were probably not made in the most suitable places, the location of the few high trees not being a matter of choice and results were again indifferent.

It appeared doubtful if it would be possible to make any practical use of this survey, when the method of drawing total anomaly vectors on suitable vertical sections was used. This method could be applied because all the elements required for a complete definition of the magnetic field of the earth had been observed. From the examination of these sections, some of which are reproduced in Figure 2, it appears that aside from a few completely erratic values which obviously can be attributed to magnetic boulders, the main anomalies are due to two different causes, (a) the small superficial masses visible on the top of the range and (b) two deeper poles, which can be considered linear and orthogonal to the plane of the sections, in a first approximation, and which are roughly parallel to each other, and to both sides of the southeastern half of the ridge of the hills. These poles have *opposite sign* and should therefore belong to a single magnetic body, which for geological reasons is supposed to be a somewhat concave "magnetic plate." The unexpected point is that this "magnetic plate" occupies roughly the position of the limestone horizon, which outcrops on both sides of the hill and belongs to the synclinal structure.

From a geological point of view, that there should be iron ore in the limestone is by no means improbable. The hill-top has all the characters of a "roof-pendant" on a granite mass, and pyrometasomatic ore deposits tend to localize in the more reactive limestones. Because a plate of magnetite of about 2.5–3 meters thickness would suffice to explain the magnetic anomalies, it has to be supposed that the limestone is only partially replaced by magnetite bodies, which at a distance may well behave magnetically like a single continuous mass.

However, field evidence of iron ores has *not* been found in the limestone, which appears only in limited outcrops covered with scree. But Auden had already remarked that part of the tremolite schist is extremely rich in magnetite. The geological *hypothesis* that the magnetic iron ore lies as a replacement product

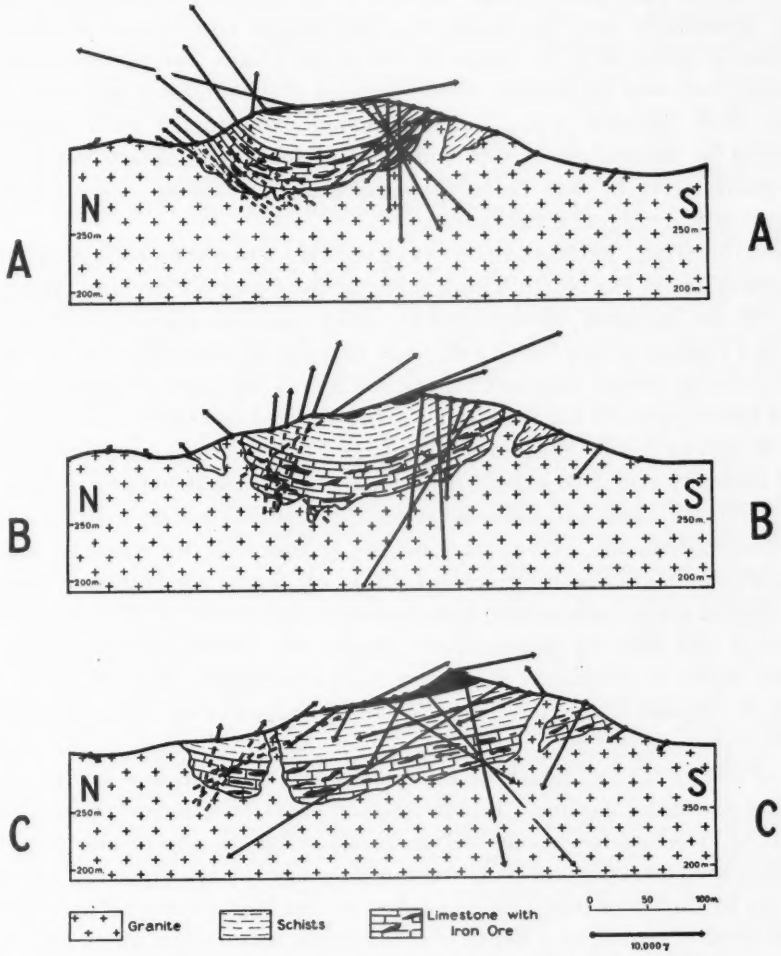

FIG. 2. Gore Iron Ore Deposit (Daltonganj, Bihar).—Schematic geological sections with total magnetic anomaly vectors.

within the limestone, may still need confirmation, but the geophysical fact remains that the anomalies are best explained by a magnetic plate conforming to the structure of the hill.

Manganese Deposits of the Central Provinces

Most of the manganese production of India comes from the deposits of the Central Provinces, where the ores form concordant beds within highly folded

crystalline schists of the Gondite Series of the Dharwar System (Archaean). The ores, like the enclosing schists, were originally sediments, and are now markedly transformed by the most intense regional metamorphism.

Fermor (1909) has described in detail their geology, economics and mineralogy which is varied and complex. Some of the so called manganese "oxides" of India apparently are, like magnetite, less simple compounds in which the same element enters both the anion of the cation phase. Fermor tried magnetic prospecting, but with indifferent results because of unsuitable equipment. About 35 years later Gulatee (1945, 1947) resumed experiments with geophysical prospecting for manganese ores in India. After some preliminary gravity work with a gradiometer he was definitely successful in a survey carried out later on with a vertical magnetic variometer.

Only one vertical magnetometer was available when the geophysical section began operations at the North Tirodi mine, of the Central Provinces Manganese Ore Co., in the Balaghat district; and the daily variation was obtained by interrupting the regular survey thrice a day and making observations at a central base station. Nothing similar was done for the horizontal component because the sensitivity of the equipment used did not warrant it. For the same reason this component as well as the declination was measured only in areas where anomalies of marked intensity could be expected because of anomalous vertical values. Two groups of North-South and East-West parallel lines 20 meters apart accurately oriented astronomically were plotted on the ground and the magnetic measurements were made at their intersections. Later on, where the results of these first measurements made it advisable, more stations were added obtaining a closer grid with points now only 10 meters apart. About two thousand stations had been measured up to the beginning of August 1948, covering an area of almost three-quarters of a square kilometer. The positive and negative vertical and horizontal anomalies that were encountered which are believed indicative of workable masses of ore at shallow depth below the surface, range from a few hundred to about two thousand gammas; but in isolated cases even larger anomalies have been found. Declination anomalies generally range to about one degree and larger ones are the exception. It is encouraging that at the time the author left India, out of the three trial pits being dug on the basis of magnetic indications, two had already struck, at a depth of five and ten meters, ore which had escaped detection in the midst of a mining field since long under exploitation.

INVESTIGATIONS BY THE SPONTANEOUS POLARIZATION METHOD

The Pyrite Occurrences of the Sone Valley, Bihar Province

These deposits occur in the Vindhyan system, one of the thickest and most extensive sedimentary formations of Peninsular India. Whereas the Lower Vindhyans are a marine facies, the Upper Vindhyans, consisting of massive sandstones thousands of meters thick, show all the characteristics of shallow

water continental deposits formed in a semi-arid environment (Auden, 1933). The pyritiferous Bijaigarh shales underlie the massive Upper Kaimur sandstone, which forms, in the area under consideration, high plateaus founded by almost vertical scarps, rising to a height of about two hundred meters. The soft Bijaigarh shales are at the base of these precipitous cliffs. The bedding of the shales and the sandstones is practically horizontal. It is clear that the Bijaigarh shales are therefore in a most unfavorable condition as far as their examination is concerned, because their outcrops are almost always covered by a thick scree of debris from the overlying Upper Kaimur sandstones. They may be seen exposed only where some gully has cut through the scree. This scarcity of exposures is responsible for the controversy whether the richer pyrite concentrations are persistent, or if they represent only lenticular concentrations.

In the first locality studied, Am Jhor, about five kilometers NNW of Banjari railway station, a pyritiferous bed less than one meter thick is found in the Bijaigarh shales about 6 meters below their top. They are visible in a gully and have been prospected for by a mining company. It is evident in the ore which has been extracted that this pyrite oxidizes and alters to sulphates in an extremely short time when exposed to the atmosphere. A spontaneous polarization survey of more than 1,200 stations was conducted around this exposure, along profiles 30 feet apart and approximately parallel to the dip of the slope. The stations were spaced every 12 feet, along the profiles and by using a long cable, the potential of all the stations was determined with respect to one and the same fixed electrode. Very strong anomalies, of the order of 1,000 mv were found on the exposure itself and in its immediate surroundings (Fig. 3). No other anomalies of any importance were encountered, not even where a boring was said to have struck the pyrite at a depth of only six meters. Apart therefore from the question which remained of how far the actual deposit extends, it must also be inferred that, with the conditions prevailing in the locality under study, such a thin seam cannot be detected even through a moderate cover of a few meters of rock boulders and scree.

Another survey was made in the "Jamunia Nala" locality six kilometers due west of Banjari railway station. Here some blocks of limonitic material lying on the surface had been interpreted by the company interested in these deposits as alteration products of an underlying pyrite seam, but this appears to be doubtful. The blocks are probably the result of a superficial phenomenon already described by Auden (1933) for this area which he calls "ferrugination," i.e., a gradual impregnation and replacement, starting from joints and cracks, of sandstones with iron hydroxide leached out by meteoric waters from the surrounding rocks. The electrical survey was extended along the slope and therefore across the strike, because the bedding is also practically horizontal, so that it must have crossed the scree-covered Bijaigarh shales, and eventual pyrite beds concealed in the same. The spontaneous polarization measurements were carried out with the same technique and spacing of stations as in Am Jhor, and again

over 1,200 stations were surveyed. Unfortunately, the work proved totally inconclusive.

It is true that erratic differences of potential up to about 100 mv were ascertained, but were extremely variable from day to day. It was not possible to make a complete study of their cause and of the causes of their variations, a study which would have been rather of academic interest. The writer would correlate them partly with the same phenomena of atmospheric electricity which account

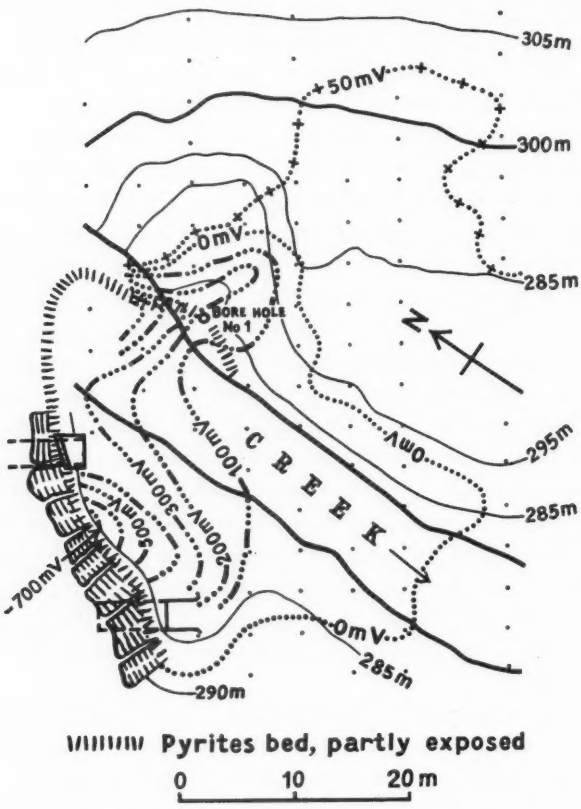

FIG. 3. Am Jhor Spontaneous Polarization Survey (Sone Valley, Bihar).—Detail of the area showing strong anomalies.

for the electrical potential gradient in the atmosphere; and partly with the effects of geological contacts between different types of rocks. These latter were noted many years ago (Hunkel, 1928) and again recently by Dickey (1943) and Mounce and Rust (1945). Also, Ramachandra Rao (1945a) has pointed out that a variety of causes besides ore bodies may cause spontaneous polarization effects.

The Graphite Deposit of Dandatapa, Athmallik State, Orissa Province

A belt of Archaean crystalline schists, known as "Khondalites," occurs near the center of the southeastern coast of India, and parallels it for about 600 kilometers. The schists are composed mainly of quartz with associated garnet and sillimanite and often also feldspar. They are evidently the products of the metamorphism of silico-aluminous sediments. They are generally associated with Archaean gneisses and granites which often invade them, resulting in hybrid rock types. A constant accessory constituent of the Khondalites is small flakes of graphite. However, as described by Wadia (1943) for the graphite occurrences of Ceylon which are associated with similar rocks, where *workable* graphite deposits occur in Khondalites, the deposits generally have the character of irregular and not at all conformable veins, and seem related to granitic and pegmatitic intrusions. A number of small graphite lodes, many of which also yield very pure flakey graphite, have been worked from time to time in this area. Remembering also the successful investigations for graphite by Ramachandra Rao in Mysore State (1945b), the area around one of these small mines, at Dandatapa in Athmallik State, was chosen for geophysical study. This study was conducted between September 1947 and March 1948.

The geophysical survey was laid out by plotting equidistant parallel profiles at either side of the mine, spaced 20 meters apart, at right angles to the general strike and therefore roughly along the slope. On each profile, stations were located every ten meters, in horizontal projection. Natural potentials were measured in the usual way with a potentiometer fitted with a sensitive zero galvanometer, and using two copper-copper sulphate nonpolarizable electrodes. One of these two, the reference electrode, was kept in the same place for the whole duration of the survey, usually without even removing it overnight. The contact of the moveable electrode with the ground was improved by *slight* watering, after which it was generally found satisfactory, the moist nature of the ground and the frequent and heavy rains having a favourable influence. A fair number of repeat stations always gave good values. About 3,000 stations were measured covering an area of about one-half a square kilometer. The results are shown on the map in Figure 4 where, because of the small scale, the individual values obtained at each station were omitted. It is realized that the assumption of a reference potential to be taken as "zero" potential is somewhat arbitrary, but it clarifies matters and facilitates visualizing the areas of marked anomalies. In the present case the arithmetical average of all the potentials measured was taken as "zero" potential, a procedure which should be fairly correct because of the large number of stations measured and located along profiles extending far into presumably undisturbed ground. The extremely big differences of potential which were found, up to about 900 mv, are quite striking.

Two well defined belts of high negative anomalies appear on the map. The geological survey of the same area confirms that these belts follow the strike of

the local formations, and must therefore be connected with some particular horizon within the same. Compared with the sharp negative anomalies the positive ones appear rather broad and poorly defined. In three of the most prominent negative centers, all on the upper of the two anomalous belts, trial trenches were cut, to a limited depth because big boulders were soon encountered. In all three trenches some graphite was found, and in the middle one, which was sunk to a depth of twelve meters, the graphite samples were associated with feldspar. They were distinctly different from the sparse flakes disseminated in the Khondalites.

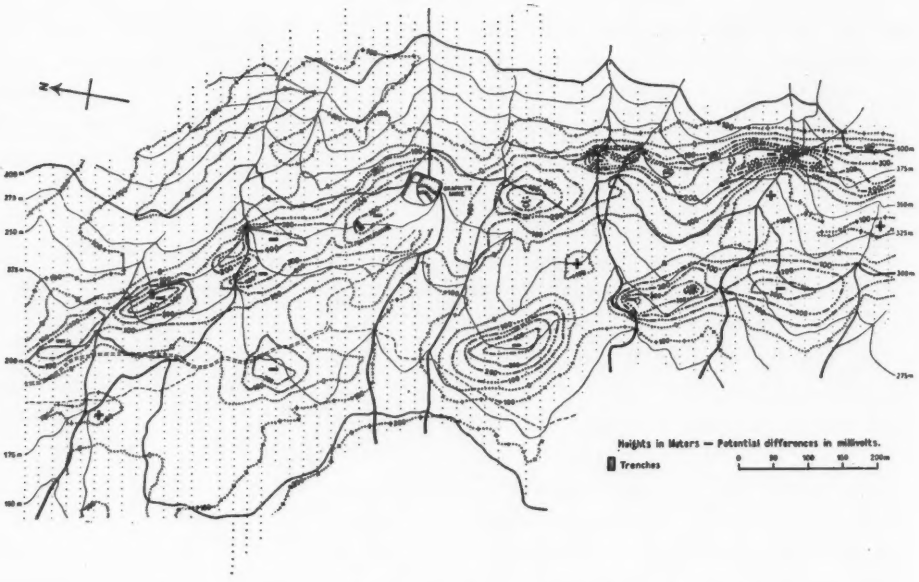

FIG. 4. Spontaneous Polarization Survey of Graphite Bearing Area at Dandatapa (Athmallik, Orissa.)

This survey has proven conclusively the usefulness of the spontaneous polarization method for indicating emplacements for exploratory workings for graphite, under conditions such as prevail in this part of India. But the writer does not believe that much more can be obtained. It would be a mistake to try to correlate the largest anomalies and the highest gradients with presumably richer parts of the deposit, because a careful perusal of the map discloses that the sharpest anomalies correspond in most cases to topographical features, like creeks, where the thickness of the overburden is reduced below the average. It is this thickness which mainly determines here the general appearance of the anomalies.

ELECTRICAL RESISTIVITY AND SEISMIC REFRACTION SURVEYS IN CONNECTION WITH ENGINEERING PROBLEMS

As far as ease of producing the necessary equipment is concerned, the electrical resistivity techniques range next to the spontaneous polarization method but have an enormous advantage over the latter because they use artificially created energy fields and can be adapted to a far bigger variety of problems. Therefore they were soon adopted by the Geophysical Section and used in preference to all other methods. Direct current and nonpolarizable potential electrodes were always employed. The Section owned, at the time the writer left its direction, four sets of resistivity equipment, of which three were completely manufactured in its own workshop.

Investigations at Maithon Dam Site and on the Barakar and Damodar River Beds (Bengal and Bihar Provinces)

The world-wide interest in the work of the Tennessee Valley Authority has also inspired India to plan multi-purpose development schemes for some of its more important river systems. One of these projects, which probably will be the first to enter the stage of practical fulfillment, is the Damodar River Development Plan (Central Technical Power Board, 1946). It aims at controlling and regulating by a group of dams the course of the Damodar River and of some of its tributaries such as the Barakar and the Ajai, which flow through the two premier coalfields of India, the Jharia and the Raniganj. The Maithon dam site on the Barakar River was one of the first to be thoroughly investigated by detailed topographical surveying, geological mapping, and churn and core drilling. It is in the Archaean country, about one and one-half kilometers upstream from the boundary with the Paleozoic rocks of the Raniganj coalfield. It is situated where the river cuts through a range of low and rounded hills and subsidiary dams will be required on the lowlands to the southwest of the river.

During the low water period in this area most of the river section, having a width of about 250 meters along the dam alignment, was occupied by a flat expanse of dry, clean, siliceous sand in which meandered a channel of shallow running water. About 50 pairs of "electrical soundings" were carried out in this sandy bed with the standard Wenner arrangement of four equidistant electrodes and always making two soundings along orthogonal alignments in every station to ascertain the homogeneity of the ground. Measurements with a fifth central electrode, "Lee configuration," were also often made for the same purpose. These soundings generally yielded typical three layer curves which resolved themselves into two layer curves, where the station happened to be located just on the edge of the water channel. It was possible to make an exact interpretation of the field curves using about 20 stations, by direct comparison with theoretical, computed two and three layer curves. Considering the various layers of the ground as defined by their electrical properties and proceeding in descending

order, one encounters first on the very surface a thin veneer, markedly affected by seasonal and meteorological variations. Its resistivity may reach, when the surface of the ground is dried and baked by the tropical sun, values of the order of 10,000 ohm-meters. This veneer can generally be disregarded in the interpretation because of its negligible thickness, but if often makes it very difficult to obtain sufficiently good ground contacts.

At Maithon as many as six copper rods in starlike arrangement had to be used for each current electrode, and although they were well watered, batteries supplying a potential as high as 600 volts were required. What therefore really corresponds to the "first layer" in the three layer resistivity curves is the sand below the surface veneer and above the level of the water in the river, sand which therefore is moistened only by capillarity. Its resistivity (ρ_1) at Maithon varies about a mean of 350 ohm-meters. The second layer is represented by the water-saturated sand extending down to the bed-rock, with resistivities (ρ_2) of 60–100 ohm-meters. This second layer should be identical with the first layer in the previously mentioned cases where the field curves approximate two layer curves. However, if one can generalize using a small number of measurements, it seems that in the two layer cases the water-logged sand shows a higher resistivity than in the three layer. Perhaps the proximity to the running water has caused some leaching out of the contents, however small, in electrolytes of the pore-water. The bottom layer is represented by the Archaean bed-rock, whose calculated

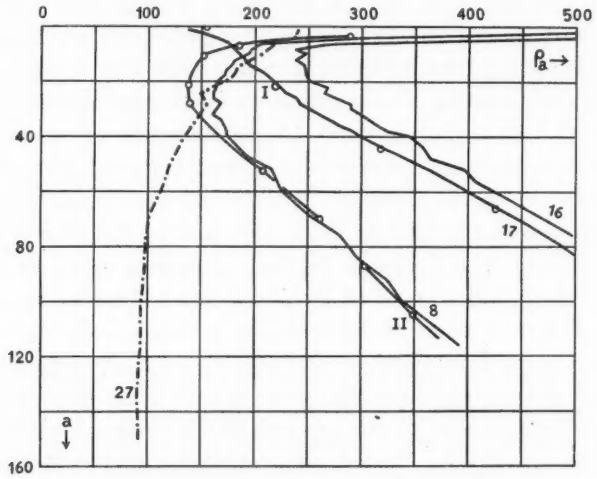

FIG. 5. Maithon Dam Site, Bengal-Bihar Border.—Some representative electrical soundings, with theoretical comparison curves. Apparent resistivities ρ_a in ohm-meters, electrode separations a in meters. For sounding 16 the computed depth to bed-rock is 23.4 meters.

Electrical soundings Nos. 8, 16 & 17—River sand & Archaeans. No. 27—River sand & Barakar sandstones. No. I—Points of theoretical curve for $\rho_1 = 155$ Ω.m, $\rho_2 = 1085$ Ω.m, $h = 22.1$m. No. II—Theoretical curve for $\rho_1 = 381$ Ω.m, $\rho_2 = 95.5$ Ω.m, $\rho_3 = 907$ Ω.m, $h_1 = 3.5$m, $h_2 = 24.5$ m.

resistivity (ρ_3) always approximates 1,000 ohm-meters. This value is in good agreement with those directly measured inside a shallow bore hole which penetrated the bed-rock in the river channel. The ascertained depths generally range between 20 and 30 meters. A few representative experimental curves, two of them together with the best fitting theoretical curves, are shown in Figure 5.

In those few instances where it was possible to verify the geophysically obtained depths by direct comparison with drilling logs the concordance was perfect. In these cases the "peak-rule" has been disproved again by giving erratic results. In most of the borings the casings were left in place with consequent apparent lowering of the resistivities and electrical depths about 30 per cent too large. But aside from these cases where an error was foreseen and even disregarding the few excellent checks on uncased borings, the electrical soundings have supplied depths which have to be considered reliable.

The study of the Maithon dam site was followed by extensive investigations, in the Jharia and Raniganj coal fields, on the characteristic resistivities of the various terms of the Gondwana formation and of the overlying alluvium; and many measurements were made above ground, and also in wells, mine workings and bore holes. But even after this amount of field data was accumulated the work of determining the electrical resistivities on the formations in and around the Jharia and Raniganj coal fields may still be improved. The electrical soundings in the Sindri area were not computed in detail during the period to which the present paper refers. The measurements in shafts and in other mine workings, although carried out on fresh exposures with the Wenner technique, are affected by local inhomogeneities because of the extremely small electrode separations necessarily adopted. Moreover, some reduction of the water content of the exposed surfaces seems unavoidable, as confirmed by the fact that the resistivity values so obtained are generally somewhat higher than those calculated from soundings. Finally, although some electrical anisotropy of the stratified formations was apparent, generally with higher resistivity values across than along the bedding, this matter was not studied in detail. However, the values which seem the most frequent and characteristic are given in Table 1.

TABLE 1

RESISTIVITIES, IN OHM-METERS, OF THE ROCKS OF THE JHARIA AND RANIGANJ COAL FIELDS

Archaean gneisses; Maithon, Sindri, Mejia areas	1,000–1,500
Barakar sandstones; Barakar and Sindri-Gansadih areas, Kumardubi bore hole, New Laikdih colliery	50–200
Barren measures (Ironstone shales); Sindri area	100–150
Raniganj sandstones; Mejia area, Banksimulla colliery	60–120
Panchet sandstones; Mejia area, about	45
River sands (lower values hold for saturated sands, higher ones for moist sands above the water table)	40–300
River Sands, uppermost sun-dried layer, very thin, up to	10,000
Alluvium and cultivated soil (very few determinations)	5–25

The Jogighopa Bridge Alignment, Goalpara District (Assam Province)

One of the fundamental problems for building a bridge over the Bramaputra River which would rank among the major structures of its kind, is that of proper foundations for the piers (Chopra, 1947). It would include deciding if the piers could be brought down to solid bed-rock or not, necessitating a knowledge of the depth of the latter below the bottom of the river. About forty wash-borings were made to a maximum depth of about 65 meters, along or near the chosen alignment, partly on sand banks and partly from rafts. Most of these borings had to be

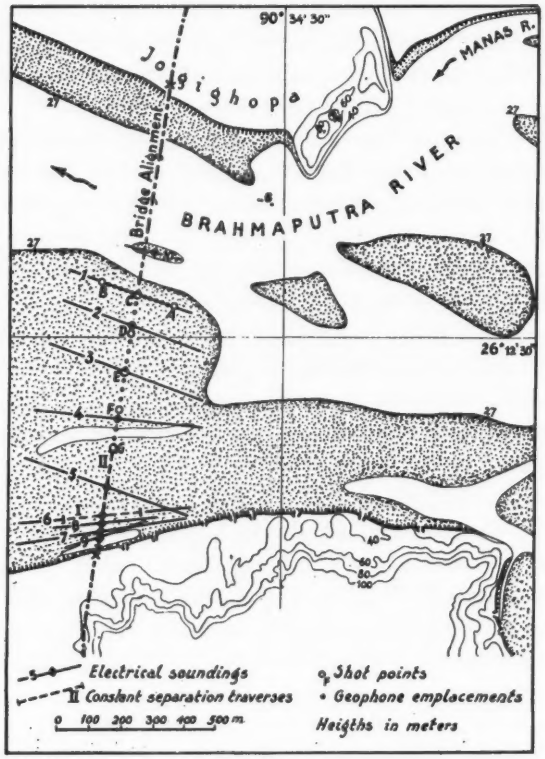

FIG. 6. Brahmaputra Bridge Project, Jogighopa, Assam. Plan at low water level (March 1948) with sketch of geophysical work.

stopped when they were evidently still in river sediments, and even of the very few which were suspected to have reached the bed-rock, only one, in the opinion of the writer, may have touched it. The Geophysical Section was requested to determine the data which borings had failed to supply. There are large seasonal variations of the water level, about ten meters between maximum and minimum. At minimum level approximately the northern half of the alignment, which from bank to bank is about 2,800 meters long, is under water, whereas the southern half is occupied by low sand-banks. Further details are seen in Figure 6. It was

impossible to make any kind of geophysical investigation in the tract covered by the swiftly running water and the survey would have to be limited to the sand-banks. These emerge to an appreciable extent only towards the end of the calendar year. At the beginning of February violent dust storms make work difficult or impossible and after about two weeks the water level starts to rise again. With Archaean rocks of exactly the same type forming the hills on both sides of the river and in the absence of other formations, it may be assumed that the bed-rock below the river is Archaean. This at once indicated the use of "electrical sounding" which had been used successfully in South India (Ramachandra Roa, 1947) and at Maithon as the method to be used, even if the depth to be expected here was much greater than in the case of the quoted investigations. Therefore the same technique as employed at the Maithon dam site was adopted. Ten soundings were made using direct current and the usual Wenner arrangement, with frequent use of the fifth "Lee" potential electrode for testing the homogeneity of the ground. Two short "constant separation traverses" were also surveyed. The curves obtained for the soundings approximate three layer curves with a very thin top layer, although sometimes there is a gradual decrease of resistivity with depth in the second layer. This is attributed to an increasing content of electrolytes with increasing distance from the running water. These curves were again interpreted by comparison with theoretical three layer curves. Two of the field curves together with the best matching theoretical ones are reproduced in Figure 7. The resistivities observed for the river sands above the water table were of the

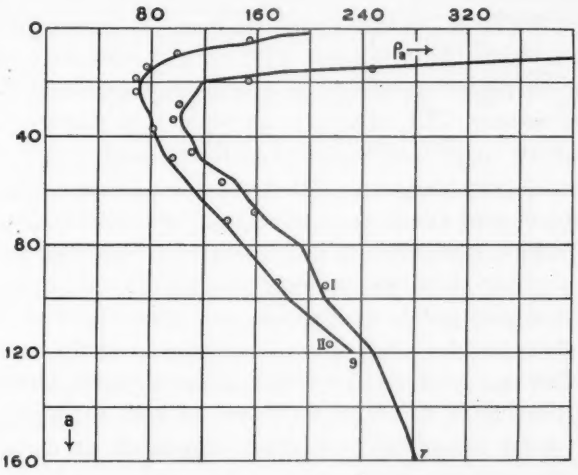

FIG. 7. Brahmaputra Bridge Project, Jogighopa, Assam.—Two representative electrical soundings, together with theoretical comparison curves. Apparent resistivities ρ_a in ohm-meters, electrode separations **a** in meters.

Electrical soundings Nos. 7 & 9. No. I—Points of theoretical curve for $\rho_1=350$ Ω.m, $\rho_2=62$ Ω.m, $\rho_3=744$ Ω.m, $h_1=5.6$ m, $h_2=22.9$ m. No. II—Points of theoretical curve for $\rho_1=190$ Ω.m, $\rho_2=54.3$ Ω.m, $\rho_3=760$ Ω.m, $h_1=4.7$ m, $h_2=32.9$ m.

order of 150–190 ohm-meters, with an anomalous value of 350 ohm-meters for sounding No. 7. The values for the middle layer of river sediments saturated with water varied between 35–62 ohm-meters, and for the Archaean gneisses of the bed-rock were of about 750 ohm-meters.

Because of the great importance of the engineering structure involved it seemed advisable to check the results of the electrical resistivity survey by another independent method, and for this the seismic refraction method was chosen. Only a military sound ranging equipment was available as a seismic recorder. It was employed for the first time by the Section on this investigation. It had only four channels, one of which had to be used for recording the shot instant. No drilling equipment had been provided by the Railway Administration, at whose request the investigation was made, for the shot holes. After one longitudinal profile had been shot, a tract of about one kilometer in length of the actual bridge alignment from the water edge southwards was explored in detail. Shot-points were located every 240 meters and geophones every sixty meters, both north and south from each shot-point, up to a maximum distance of 660 meters in certain cases.

Pits were dug for shot holes in the loose sand to slightly below the water table. This sometimes necessitated going to a depth of seven meters. Then a casing, made of the stem of a palm tree or bamboo split hollowed and joined again, was put in place and the pit filled up. The quantity of explosive (gelignite) used varied from a few ounces to more than five pounds according to the distance. The small diameter of the casing prevented the use of larger quantities which have been desirable because of the tremendous attenuation with distance which was characteristic for the sand. The charges were detonated electrically and a telephone earpiece was placed on the ground near the shot-point for recording the shot instant. The reluctance geophones, miniature Benioff types, as described by Bullard (1938) and Bullard and Kerr-Grant (1938) were arranged in shallow holes in the sand about one-half meter deep. For the sake of convenience these shot-points, spaced every 240 meters, may be considered as pertaining to three distinct profiles, each shot up and down from two shot-points 480 meters apart, the first and the third profile being contiguous and having a shot-point in common and the second profile overlapping with the other two. The travel-time graph of one of these profiles is reproduced in Figure 8 together with its interpretation. The specialist may be shocked by the number of points which fall outside the straight travel-time lines which were drawn as best fitting the experimental results; but he must remember how much expanded, as compared with conventional refraction surveys, both scales of the graph must be for such a shallow investigation. Furthermore the bed rock most probably does not have the broad uniform geometry of oil structures and the first layer of river sediments is by no means homogeneous. Notwithstanding the work involved the travel-time curves in best agreement with the experimental results were also computed in some cases by the least square method, always under the surmise that they consisted

of two straight segments. Although the results were somewhat different it is doubtful if, at least in this case, the additional effort is justified.

The positions and slopes of the segments of the travel-time curve referring to the first layer are well defined by using the excellent "second arrivals." But the writer sometimes doubted that the second segment of the curves should be split up again in two segments corresponding to two different velocities. In this connection he must admit that the very first profile, shot up and down in approximately an East-West direction through the northernmost shot-point of the

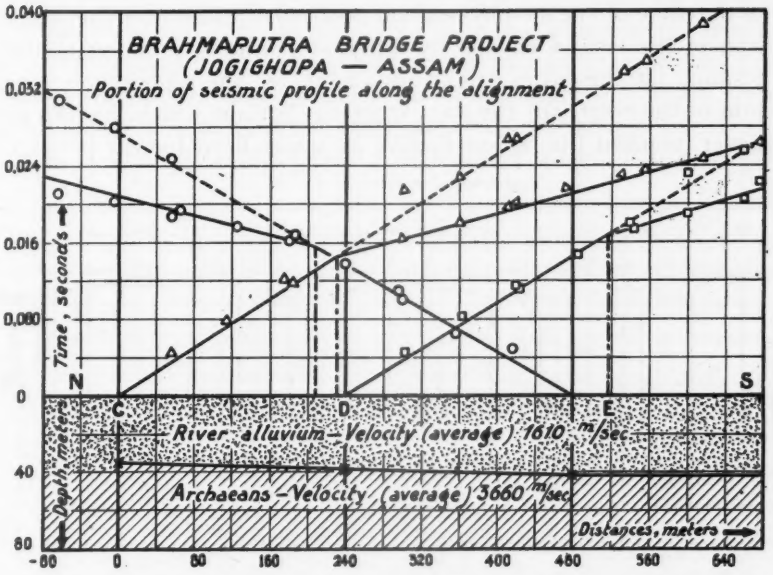

FIG. 8. Brahmaputra Bridge Project.

North-South set of profiles, has yielded for the second layer a velocity of 5,290 m/sec, as compared with 3,660 m/sec, average of three pairs of values ranging from 3,220 to 4,280, from the three North-South profiles. The writer would not dare to attribute such a difference only to an anisotropy of the crystalline schists of the Archaeans. The velocity for the first layer was found to be 1,610 m/sec, average of eight values, ranging from 1,430 to 1,730. No "weathered layer" worthy of being taken into account was encountered, as was to be expected if one remembers the local conditions.

With respect to the eventual variations of velocity in the upper layer of river sediments, it may be recalled that the boring records show that the grain size increases with depth from silt and sand to cobbles and boulders. Other conditions remaining equal, this may not influence the electrical conductivity but may affect the elastic constants. The electrical conductivity does in fact depend primarily only upon the pore volume filled with the conductive water. This pore volume is independent of the size of the grains if only their shape and arrangement

remain constant. However, the writer is not so sure that the number of surfaces of discontinuity between grains and water ought not to affect the velocity of the elastic waves. In the meantime reference is made to a recent statement (Burwell, 1940) that the wave velocity, fairly constant in a certain area for more or less fine-grained saturated alluvium, increases for glacial till.

The Railway Administration had agreed that at least one bore hole would be sunk immediately at a point to be chosen by the geophysicists, so that they might check their findings and determine local constants before submitting a report. But as it seems now highly uncertain if and when this bore hole will be sunk, the outcome of the geophysical surveys, unadjusted and checked only by comparison of the results yielded by different methods, is herewith described. Figure 9 shows for the entire bridge alignment, (a) the topographical profile of the bottom of the river, (b) the data from the borings which, having never, or almost never, reached the bed-rock, give an upper limit for the position of the

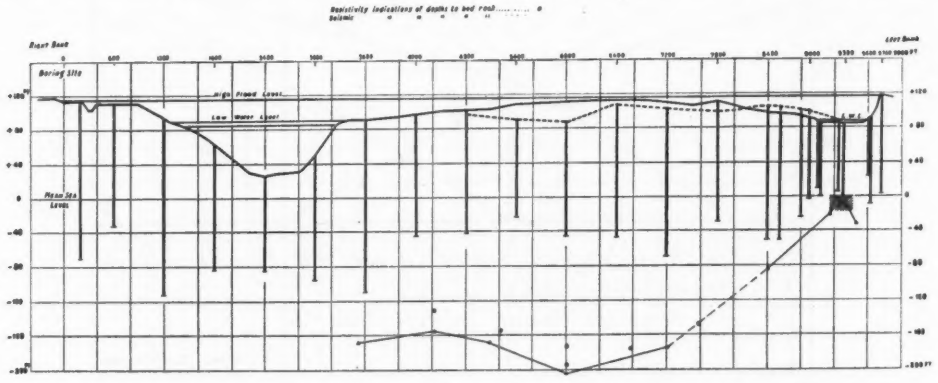

FIG. 9. Brahmaputra Bridge Project, Jogighopa, Assam. Section along the bridge alignment showing the topographical profile, the borings, and the position of the bed-rock as determined by electrical and seismic methods.

latter, and (c) also the depths as yielded by the two different geophysical techniques. On the same perpendicular two different seismic depths are given. They were obtained from two independent profiles recorded to the north and to the south of the same shot-point. On the whole, agreement seems quite satisfactory and the results in any case are sufficient for their purpose, namely, to decide if foundation on rock would be possible. It is *not*.

ELECTRICAL RESISTIVITY INVESTIGATIONS RELATING TO THE ECONOMIC GEOLOGY OF COAL BEARING AREAS

The coalfields of India, which appear as detached inliers in the midst of Archaean areas, correspond to down-faulted troughs whose gradual subsidence permitted the accumulation of enormous thicknesses of fresh-water Gondwana sediments. Although the present pattern of the coalfields may not always cor-

respond to the original deposition trough, still their external boundaries are very often marked by steep fault planes. As the Archaeans on the other side of these faults have a markedly higher resistivity than the coal measures, there appeared to be a distinct possibility of differentiating between the two formations, to delineate their boundaries.

The Kamptee Coalfield (Central Provinces)

The location of this field (V. R. Khedker, unpublished report, 1945; E. R. Gee, unpublished report, 1946) is seen in Figure 10. On this map all the geological surface evidence, as carefully surveyed by Cotter and Bhattacharji (unpublished geological maps, 1919–1923), is reproduced. It will be noticed how extremely scarce the outcrops are, most of the area being uniformly covered by a thick layer of soil and alluvium. When it was decided to conduct a geophysical survey in this area, it seemed certain that an extensive boring campaign would soon

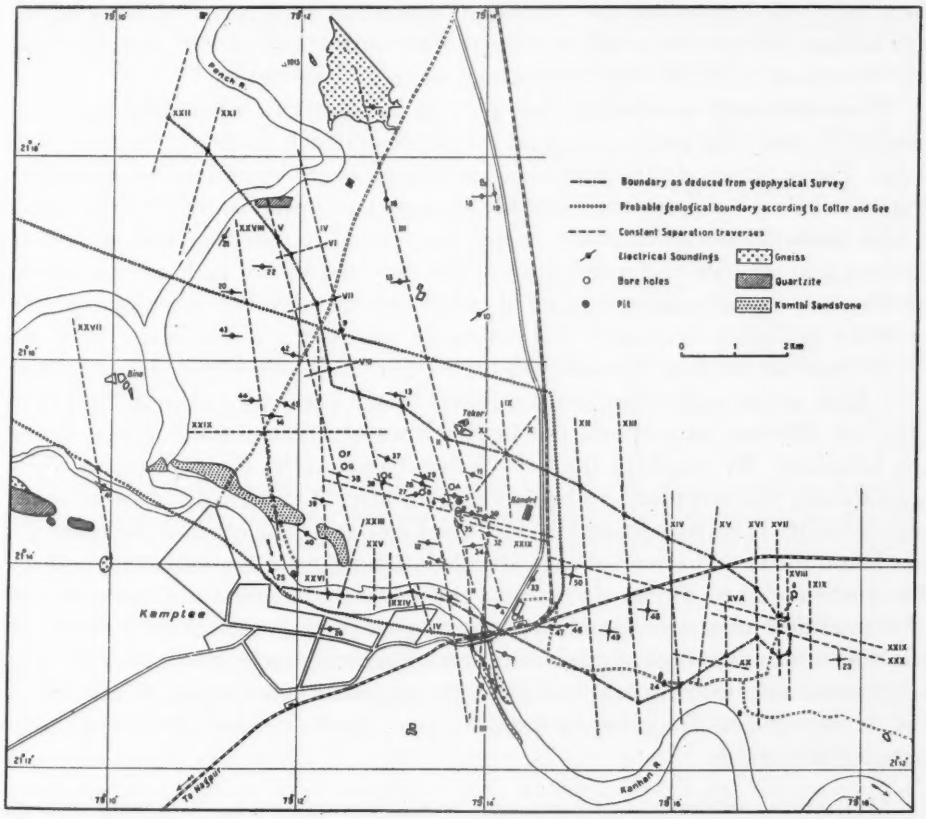

FIG. 10. Electrical resistivity survey of Kamptee Coal Field Area, Central Provinces. Map showing geology, bore-holes for coal, location of "electrical soundings" and "constant separation traverses," and boundary of sedimentary area as determined geophysically.

be started for the exploration of the area under consideration. Therefore, it appeared useful to map first by geophysical means the alluvium-covered boundary between the Gondwanas and Archaeans, so that useless drilling outside the sedimentary area might be avoided. Most of the area to be surveyed is under cultivation, quite flat and therefore well suited for electrical resistivity methods. After a certain number of electrical soundings had been made for collecting data about the resistivities of the various formations, the measurement of long "constant separation traverses" was begun. They were made as far as possible at right angles to the supposed boundary, in the hope that the change from one formation to the other would be well defined and that some information about lithological changes within the sedimentary area itself would be obtained. The low surface resistivities with their screening effect proved very misleading. It was only after the geological untenability of some geophysical misinterpretations had become apparent to the geophysicists, that "separations" of exceptional length as compared with the depth of the first interface, bottom of the alluvium, were adopted. Thereafter the "constant separation traverses," totaling about 110 kilometers were generally measured with separations of 120, 210, and 300 meters and occasionally with separations of 30 and 60 meters.*

With such large separations the increase in resistivity when crossing a discontinuity was frequently so gradual that it was difficult to define the boundary point. The accuracy of this determination was improved by measuring separately the two "halves" of each four-electrode arrangement in the boundary area, using a fifth potential electrode at the center, i.e., the "Lee partition method." It is evident that whereas the resistivities of the two "halves" of each setting should be identical in homogeneous ground, they become different when the profile crosses a geological boundary. The difference will become a maximum when one "half" is all on the first formation and the other "half" all on the second formation. If in a first approximation we disregard the effect of a sloping boundary plane on different separations, this occurs when the central point is just above the boundary. By graphing the two "halves" separately, their diverging when approaching the boundary and joining again after a certain distance becomes very evident. The quotient obtained by dividing one by the other of the resistivities found for two "halves" of each electrode arrangement may also be graphed. The curve obtained which, always with the above limitation, shows a maximum or a minimum over the boundary, is analogous to the "ratiometer" curve. It has the added advantage of a more accurate measuring technique, and of having ascertained also the absolute values of the apparent resistivities. Examples of the various graphs are given in Figures 11, 12, and 13, which deserve a more detailed discussion.

* For avoiding ambiguity, it may once again be clearly stated that the "separation" referred to here, generally called a when speaking of Wenner soundings, is the distance between any two contiguous of the four equidistant electrodes which, in surveying "constant separation traverses," are shifted all together in the same direction along the profile.

The upper part of Figure 11 shows a portion of a group of "constant separation traverses" measured along the same profile (No. III) with different separations, at a point where the traverses are crossing over the northern boundary from the sedimentary area into the Archaeans. The boundary has been assumed to coincide with abscissa north-540 meters. The low resistivity of the near-surface is evident, as is its masking effect on the geological boundary. However, it is

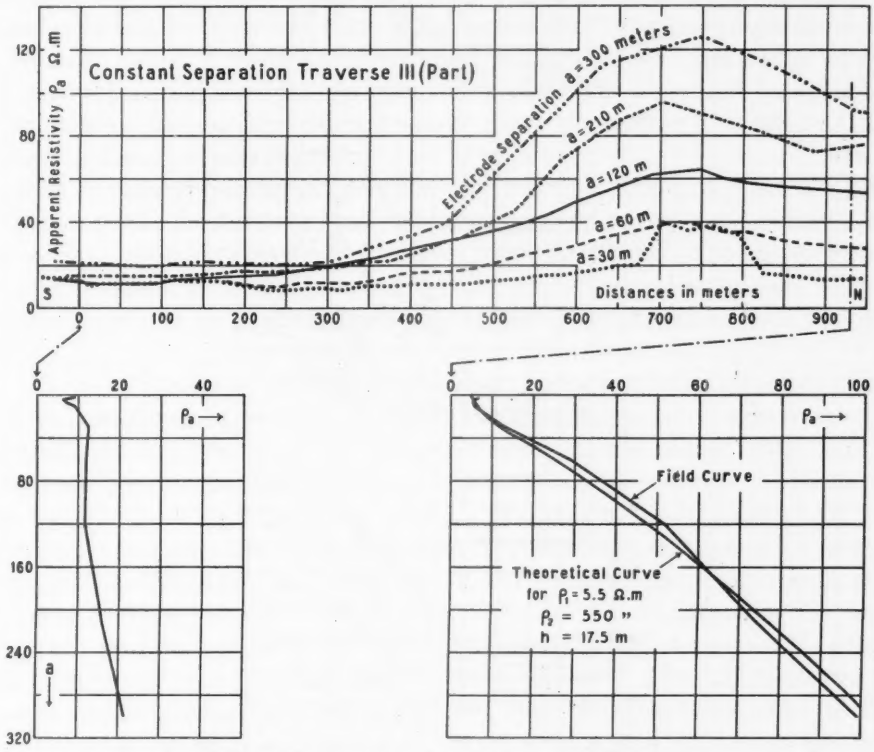

FIG. 11. Electrical survey of Kamptee Area, Central Provinces. On the top, portion of "constant separation traverses" No. III, where they cross the northern boundary of the sedimentary area and at the bottom, two "electrical soundings" along the traverses, one in Gondwanas and one in Archaeans, the latter with theoretical comparison curve.

well defined on the traverses measured with the larger separations. The "hill" on the curve referring to the smallest separation and which was noted also on some of the parallel traverses is interpreted as due to a superficial, even if hidden gravel bed. It is probably an old abandoned channel of the Pench River.

In the lower part of the figure are shown, in the usual way, two "electrical soundings", coinciding with abscissa 0 and abscissa North-930 of the profile. The first of the two soundings, entirely in a sedimentary area, exhibits the characteristic low resistivity of the Gondwanas. The second sounding, completely in the Archaeans, matches fairly well with a theoretical curve, also shown, which gives

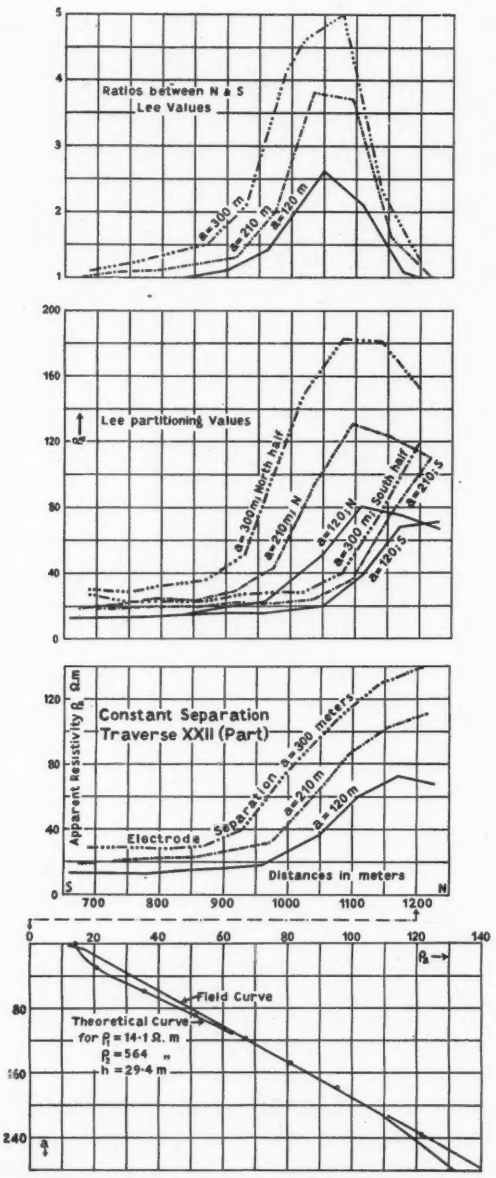

FIG. 12. Electrical Survey of Kamptee Area, Central Provinces.—Where the "constant separation traverses" No. XXII cross the northern boundary (3rd graph from above), the two "Lee values" for each traverse and station show their maximum divergence (2nd graph from above), as appears even clearer from the graphs (topmost) giving their ratio. At the bottom, an electrical sounding along the traverses, in Archaeans, with theoretical comparison curve.

a thickness of 17.5 meters for the alluvial cap based on its resistivity of 5.5 ohm-meters. The resistivity of the underlying Archaeans is one hundred times the latter value.

The third graph, counted from the top downwards, of Figure 12 shows, like Figure 11, three traverses with constant but different separations along the same profile (No. XXII), crossing again over the northern boundary between sedimentary and crystalline formations. The effect of the boundary, which is supposed to be at abscissa North-1080, is perceptible already on this graph. However, it is much clearer in the next upper graph where the two "Lee Value"-curves for each separation show the maximum divergence just above the boundary. It is still more evident on the topmost graph giving the quotients of the two "Lee values" for each separation.

The bottom graph shows again an electrical sounding at a point along the traverses to the north of the boundary and therefore in Archaean country. The theoretical two-layer curve which rather closely approximates the experimental finding is drawn for a resistivity of the alluvium of 14.1 ohm-meters with its thickness equal to 29.4 meters, and for a resistivity of the Archaeans of 564 ohm-meters.

Figure 13 illustrates the same principle of the two previous ones but with a less well defined example. It is included to show one of the many cases which may be encountered in practice. The "constant separation traverses" (No. XXIII) cross here from sedimentary to Archaean, at about abscissa North-360, the southern boundary, which happens to occur in the bed of the Kanhan river. The alluvial cover is very thin here and therefore the resistivity values increase sharply in magnitude. However, still farther south and with Archaeans all around, they decrease to very moderate values. The explanation is supplied by the topographical conditions shown in the figure. After having crossed the river the profile has to climb its steep southern bank. The thickness of alluvium therefore increases suddenly and considerably with the usual masking effect. This is confirmed by the sounding at abscissa South-263 which, analyzed with the help of a theoretical curve, reveals the usual values for the resistivities of Archaeans and overburden, but an exceptional thickness of over 35 meters for the latter.

Admittedly the big "separations" which had to be used because of the low surface resistivities blur somewhat the sharpness of the boundary determinations. This cannot be avoided being inherent in the physical principles of the method employed which averages out the resistivities over a portion of the ground whose linear dimensions are proportional to the "separations" used. If the boundary plane is inclined, there should be also some lateral shift between boundary points as found with different separations. Still it is felt confidently that the eventual uncertainty about the exact position of the boundary point should in most cases not be more than 50 meters and almost always within 100 meters. The precision should be higher in the western part of the survey than in the eastern one where the thickness of the overburden increases, and where

the width of the sedimentary area decreases to such an extent that towards its tip any measurement on one of the boundaries is already affected by the proximity of the other. Details are best seen on the map, where the boundary as determined by geophysical means is represented by lines and dots. This boundary is composed of segments which as a first approximation can be considered straight.

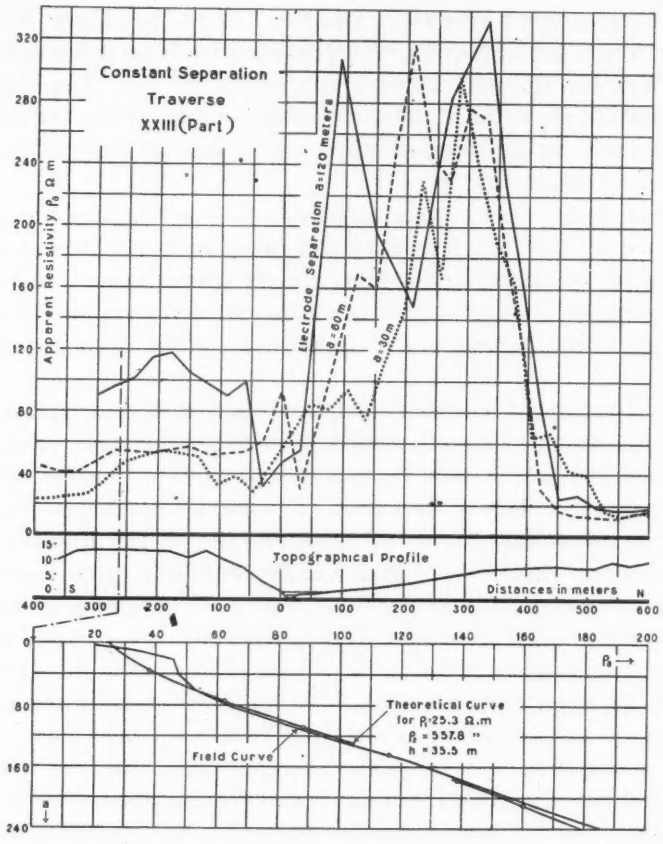

FIG. 13. Electrical Survey of Kamptee Area, Central Provinces.—"Constant separation traverses" No. XXIII crossing the southern boundary between Gondwanas and Archaeans. On the evidence of this change are superimposed the effects of the rugged surface topography. At the bottom, an "electrical sounding" in Archaeans, with theoretical comparison curve.

This would agree with the fact that the Gondwana troughs are very often limited by intersecting faults. Thus, an eventual extension of the long boundary segment running NNW-SSE in the upper left quarter of the map would pass somewhat to the East of the two barren bore-holes *F* and *G*. It would therefore correlate with the cross-fault postulated by Gee for explaining the absence, in these bore holes, of the coal seam, which had been struck in all the holes farther to the east. Moreover, the direction of the boundary segment would be roughly

parallel to the strike of the fault which, according to Cotter's surveys, cuts the Archaean outcrop on the top center of the map.

After the preliminary experiments, constant separation traversing was adopted as the standard procedure. Many more electrical soundings were made as a check on the traverses and to obtain some more details about the subsurface formations. In all, about 50 soundings were made using separations of 300 meters and more. Several of the soundings were surveyed twice with the same center but along approximately orthogonal alignments for detecting eventual inhomogeneities of the subsurface. Additional representative values of resistivities and thicknesses of overburden are shown in Table 2. The overburden consists essentially of recent fluvial sediments, but its top portion is a loamy, sticky, heavy soil, akin to the typical "black soil." The water table is at shallow depth and the resistivities found for the overburden range between three and 100 ohm-meters, values between three and 20 being by far the most frequent ones. Four out of five soundings in Table 2 are from Archaean areas whereas the majority of the soundings was actually carried out within the sedimentary belt. This is due to the variable and low resistivities of the sedimentary rocks, which were of the same order as the resistivities of the overburden. Therefore, a well defined differentiation between these two formations is seldom possible. As shown by soundings and traverses, there are fairly large variations in the resistivities of the sedimentary rocks with computed values ranging between 10 and 80 ohm-meters. Such widely differing values cannot be attributed to one single stage of the Gondwanas, but they indicate different stages in lateral sequence. Therefore, every effort was made to unravel with the help of resistivity measurements the structure of the sedimentary area by means of a considerable number of traverses

TABLE 2

RESULTS OF SOME ELECTRICAL SOUNDINGS IN THE KAMPTEE AREA

Sounding No.	Resistivities in ohm-meters Of overburden	of rock-floor	Depth to solid rock, meters	Nature of rock-floor
9	8.4	614	20.0	Gneiss (Archaean)
10	4.6	607	26.4	Gneiss (Archaean)
14	5.6	40.3	16.2	Sandstone (Gondwana)
17	7.5	592	7.3	Gneiss (Archaean)
19	4.9	277	7.9	Micaschist (Archaean)

and soundings within this area itself. However, this attempt had little success, partly because of the often mentioned "blurring" effect of the low resistivity upper layers. The coal seam probably revealed itself in sounding No. 27, and perhaps also in a few neighboring ones, by resistivity values somewhat **higher** than the average. However, as compared with other irregularities of the curves the effect of the coal is not marked enough for use in prospecting for it. This practical failure in such an apparently favorable case of a coal seam of at least six

meters thick at 45–65 meters depth, constitutes a sad commentary on the possibilities of prospecting electrically for coal.

The resistivities of the Archaeans generally vary within a narrow range, between 550 and 600 ohm-meters, but there are exceptions. For example, in sounding No. 19 a depth to the Archaean floor of about eight meters was computed together with a resistivity of 277 ohm-meters only. A nearby waterwell under excavation showed a thickness of the soil-cap of 7.5 meters and the Archaean rock at its bottom was a soft, altered and very micaceous schist of a completely different character from the hybrid gneisses of all the other local outcrops of Archaeans. Therefore, besides the gneisses and quartzites shown on the map, other lithological types of Archaean rocks occur and softer varieties have obviously less chance to be preserved in the outcrops. This survey has also confirmed toward the northern end of traverse No. III (see map) the existence of two hidden quartz veins or silicification zones in the Archaeans. They had been suspected because of the abundance of debris of spongy quartz scattered in the fields. Figure 14 clearly demonstrates how one of these veins shows up on the "constant separation traverses" by causing conspicuous bumps on the same.

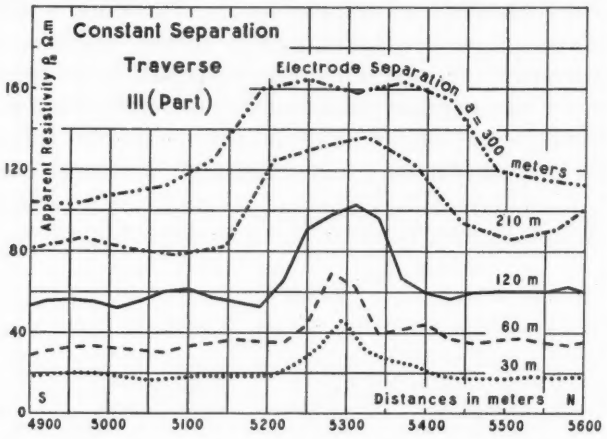

FIG. 14. Electrical Survey of Kamptee Area, Central Provinces.—A hidden quartz vein amidst Archaeans appears on the "constant separation traverses" No. III.

INSTRUMENTATION

Electrical Equipment

It is not proposed to describe in detail all the equipment used, but to mention only some special features which may be of interest. Most of the work of the Section was done, during the period under consideration, by d-c electrical resistivity methods. The instruments are of the usual type, a calibrated slide-wire potentiometer being used for measuring the differences of potential and several ranges, between 150 and 1,200 millivolts full-scale reading, being provided. An auxiliary potentiometric arrangement allows to compensate for any residual dif-

ferences of potential between the potential electrodes before current is applied to the ground. The current itself is measured by a big multi-range type millammeter, with several ranges from 10 to 2,000 milliampères full-scale reading. The Geophysical Section aimed, as far as the physical measurements were concerned, to remain within a maximum error of 1 per cent. An electromagnetic brake enabling the operator to block the needle of the ammeter at the instant he deems compensation to be reached, was under field trial. This care in the measurements partly accounts, in the writer's opinion, for the smooth electrical sounding curves which often were so smooth as to seem faked, and for their perfect reproduction when a sounding was repeated.

The instruments are characterized by an element of such detail as is feasible only in one's own workshop. An air-tight silica-gel-dried metal case carries the panel with its fittings. It is suspended elastically in an outer wooden case. All the electrical contacts are clad with precious metals. It is significant that instruments were used in double shift daily for months during monsoons, practically without a single breakdown.

The electrical current to be sent in the ground was obtained from batteries of small dry cells, of the size normally used in standard searchlights. Apart from the fact that their use is so convenient as compared with generating sets or storage batteries, that it is worth the higher expense, it was often made almost imperative by the high voltages required. In a tropical country like India even taking the utmost care in lowering as far as possible the resistance of earth contacts by using multiple current electrodes, watering them, etc., it is not rare at all that the over-all resistance of the current circuit is of the order of ten thousand ohms or even two or three times this amount.

Seismic Equipment

A piece of military equipment, a recorder developed for sound ranging purposes, was used together with its amplifiers in the only seismic investigation carried out so far (August 1948), by the Geophysical Section. The chief reason for the use of this non-standard equipment was that it had been possible to obtain it at a few days' notice from the British War Department, whose kindness is gladly acknowledged. The non-photographic recorder has as its main components permanent magnet moving coil galvanometers of exceptionally heavy construction, having taught-ribbon suspensions and long writing styluses. With almost critical damping and with a natural frequency of 70 c.p.s., they are said to have a uniform response up to frequencies of 100 c.p.s. They have a high power consumption, but provision for this is made through the high gain push-pull amplifiers which are part of the equipment. The four writing styluses—the instrument has four channels—are kept at a potential of about 500 volts with respect to the drum over which the recording paper travels. This specially prepared electrically conductive black paper, "Teledeltos paper," has a thin white coating which is burned away by the high potential current, so that the styluses leave a sharp

black trace. The paper is 75 mm. wide and the amplification has to be regulated so that the amplitude of each record should not exceed about 15 mm. A set of three fixed styluses, periodically charged at a high potential by an electronic oscillating circuit, produces on the paper time-marks in the form of three parallel rows of black dots.

The absence of photographic developing and the fact that the seismic record is immediately visible has its advantages, particularly with inexperienced crews. Moreover the equipment is small, sturdy and relatively cheap, and is provided with a 12-volt storage battery power-supply unit. One of its drawbacks is that it has only four channels, but their number could be increased in a new design. A worse defect which did cause many difficulties to the geophysical party is the fact that, because of all the high-potential sparking at the recording and at the time-marking styluses and because of the high amplification, it was sometimes difficult to keep down interferences and spurious pick-up between the several channels and between these and time marking.

The instrument has two paper speeds, five and fifteen cm./sec., and the time marking device uses a frequency of 66.7 c.p.s. This seemingly odd figure has evidently been adopted because of the velocity of sound in air, the apparatus being part of a sound-ranger.

The manufacturers (Henry Hughes & Sons Ltd.) are said to have now developed several types of such recorders for the civilian market, and another British firm (Pye-Granta Works) to supply amplifiers and geophones for use with these recorders.* The military sound-ranging recorders have already been used for shallow seismic refraction investigations by Coster and Gerrard (1947a and 1947b).

ACKNOWLEDGMENTS

The absolute freedom, limited only by supply difficulties and by force of circumstances, allowed the writer in the choice of the problems to study, in the selection of equipment, and in the organization of the field activities, has been a privilege whose value he has always been fully aware of and for which he is sincerely grateful to the Directors of the Geological Survey of India under whom he has served, and to his other Superior Officers. This point could not be ignored also because of its corollary, namely, that the writer is responsible for any shortcomings in the planning and in the execution of the work. To A. Del Carlo, the technician in charge of the workshop where most of the geophysical equipment has been produced and who in the beginning, still a prisoner of war and under the most trying circumstances, volunteered to work so that a friend may not be in difficulty, the writer is deeply indebted.

Geophysical prospecting is team-work, and it is clear to those conversant with it that in describing the investigations carried out the writer has spoken

* It has however been impossible to obtain from the manufacturers any further details, besides the short descriptions in their advertising leaflets.

also on behalf of the dozen of physicists and geologists who have collaborated with him, of the surveyors, of the workmen, of all the young people in whom he found enthusiastic and intelligent helpers. Among them he would like to mention specially L. N. Kailasam, the first physicist who joined the Section and to whom the majority of the interpretations of electrical resistivity measurements are due.

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PATENTS

O. F. RITZMANN*

In accordance with a directive from the S.E.G. Council at its meeting in April 1950, the list of abstracted patents is herewith being substantially abridged. Beginning with this issue of *Geophysics* only those patents are abstracted which relate directly to geophysical prospecting or geophysical well-logging operations. These are classified under the following broad headings, namely, electrical prospecting, geochemical prospecting, gravimetric prospecting, magnetic prospecting, seismic prospecting, well logging, and miscellaneous.

In order to afford an opportunity for further study by those who may have a continued interest in the larger number of patents more remotely related to geophysical prospecting methods and apparatus, these patents are currently being selected from the Official Gazette of the U. S. Patent Office and are here listed for reference. The abstracted patents are included in this list and are marked with a small (a). Each patent number is followed by one or more subject classification numbers corresponding to the classification system previously used (see *Geophysics*, Vol. XV, No. 3, July, 1950). Copies of these patents have not been examined and the subject classification is made only from the meager listing in the Official Gazette.

The subject classifications or the abstracts are not to be construed in any sense as an interpretation of the patents.

GRAVIMETRIC PROSPECTING

U. S. No. 2,504,604. J. D. Tear. Iss. 4/18/50. App. 7/1/44. Assign. The Sperry Corp.

Stable Vertical Mechanism. A gyro vertical for use on shipboard and which is corrected for fore-and-aft accelerations and turning of the ship by having an inertia wheel mounted on the gyro case and rotated on a fore-and-aft axis at a speed proportional to the ship's speed.

U. S. No. 2,511,869. F. E. Null. Iss. 6/20/50. App. 3/27/47.

Stabilized Vertical Pendulum. A stabilized pendulum having auxiliary pendulums with piezoelectric or photoelectric acceleration detectors whose outputs control motors to overcome the effect of the accelerations on the main pendulum.

MAGNETIC PROSPECTING

U. S. No. 2,509,394. R. Kinslow. Iss. 5/30/50. App. 12/31/46. Assign. U. S. A.

Vacuum Tube Flux Meter. A method of measuring magnetic field strength by inserting into the field a triode so that its electrostatic field is perpendicular to the magnetic field and observing the plate voltage required to maintain a predetermined value of plate current with grid bias and cathode voltage fixed.

SEISMIC PROSPECTING

U. S. No. 2,503,904. C. G. Dahm. Iss. 4/11/50. App. 6/30/44. Assign. Socony-Vacuum Oil Co., Inc.

Seismic Prospecting Method. A method of reflection shooting in caliche-covered areas by locating a velocity interface in the caliche layer with preliminary shots and then burying the geophones in holes below the interface for recording the reflection shots.

U. S. No. 2,507,230. W. R. Stinnett. Iss. 5/9/50. App. 1/21/44.

Weight Controlled Seismograph Combustion Deflection. A seismograph shot-hole loading tool having at its lower end a massive steel weight to resist the upward force of the explosion and having spring-actuated latches which engage the end of the casing for recovering it.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,508,677. G. B. Loper. Iss. 5/23/50. App. 3/20/46. Assign. Socony-Vacuum Oil Co., Inc.

Attenuation Control Circuit. A seismograph avc system in which a push-pull transformer and two tubes form a bridge circuit with the output impedance in one diagonal and with the tubes normally unbalanced and brought closer to balance by a d-c on their grids to reduce the signal amplitudes.

U. S. No. 2,509,651. R. W. Olson. Iss. 5/30/50. App. 7/15/47. Assign. Geophysical Service, Inc.

Seismograph Compositing System. A system for mixing seismograph signals at the recorder in which the amplifier output is applied to the diagonal of a bridge network with the galvanometer in one arm and the signal across the other diagonal fed to the adjacent channel.

WELL LOGGING

U. S. Re. 23,226. (Orig. No. 2,133,776). J. C. Bender. Iss. 5/9/50. App. 2/18/36, 10/18/38 and 10/4/40. Assign. Lane-Wells Co.

Subsurface Prospecting Device. A well-logging system in which the variation in radioactive properties of the formations is measured at various depths.

U. S. No. 2,504,888. A. J. F. Siegert and B. E. Watt. Iss. 4/18/50. App. 12/27/46. Assign. Texaco Development Corp.

Radioactive Borehole Logging. A radioactivity logging system in which the formations are exposed to gamma rays and the induced neutron activity detected.

U. S. No. 2,506,149. G. Herzog. Iss. 5/2/50. App. 10/19/46. Assign. Texaco Development Corp.

Well Logging. A radioactivity logging system using a number of radiation detectors carried on a moving belt in the well apparatus with their respective signals given a compensating time displacement in the recording process so that signals from a given formation are added.

U. S. No. 2,507,351. S. A. Scherbatskoy. Iss. 5/9/50. App. 11/23/45. Assign. Well Surveys, Inc.

Transmitting of Information in Drill Holes. A system for transmitting data from a well-logging sonde to the surface by varying the timing of u-h-f electromagnetic impulses impressed on an antenna and picked up by an antenna at the surface.

U. S. No. 2,508,772. B. Pontecorvo. Iss. 5/23/50. App. 10/31/42 and 9/12/45. Assign. Well Surveys, Inc.

Method of Geophysical Prospecting. A method of radioactivity logging in which the formations are irradiated by gamma rays and the variation of secondary radiation observed with a string of spaced detectors whose signals are sequentially selected by a motor-driven switch and separately recorded at the surface through a synchronously-rotating switch.

U. S. No. 2,509,908. K. C. Crumrine. Iss. 5/30/50. App. 3/28/45. Assign. The Texas Co.

Radiological Well Logging. A neutron logging apparatus in which the effect of well fluid is eliminated by surrounding the instrument with a sleeve of aluminum which nearly fills the annular space around the instrument housing.

U. S. No. 2,512,020. G. Herzog. Iss. 6/20/50. App. 3/21/45. Assign. The Texas Co.

Radiological Well Logging. A radioactivity well-logging system using a shielded neutron source and gamma-ray detectors above and below the source whose signals are separately recorded.

U. S. No. 2,513,086. R. E. Fearon. Iss. 6/27/50. App. 12/27/39. Assign. Well Surveys, Inc.

Well Survey Method and Apparatus. A well-logging apparatus arranged so that the signal representing the parameter which is logged modulates the amplitude of an oscillator whose output, together with that of an unmodulated oscillator, is transmitted through the ground to receiving apparatus which records the quotient of the signals at the surface.

MISCELLANEOUS

U. S. No. 2,503,111. E. C. Higgins. Iss. 4/4/50. App. 3/30/49. Assign. Higgins, Inc.

Amphibious Vehicle. A marsh buggy having drum-shaped buoyant wheels with extensible eccentric shafts on which may be mounted stepper plates for use in soft mud.

U. S. No. 2,504,454. C. O. Rothweiler. Iss. 4/18/50. App. 3/11/48. Assign. David White Co.

Leveling Device. A dust-proof leveling screw for field instruments having a cylindrical apron extending upward from the adjusting head into an annular recess between the instrument leg and a replaceable threaded bushing.

U. S. No. 2,509,818. H. S. Gray. Iss. 5/30/50. App. 2/2/48. Assign. W. & L. E. Gurley.

Dust Protected Screw. A dust-proof leveling screw for field instruments having an internally-threaded sleeve in which the screw works and a floating protector sleeve extending upward from the adjusting head and which telescopes around the threaded sleeve.

U. S. No. 2,511,855. W. G. Keck and S. A. Fry. Iss. 6/20/50. App. 4/2/47.

Thermoelectric Feedback System. A system for compensating drift in a low-frequency signal using a d-c amplifier whose output is fed to a thermocouple-heating unit with the thermocouple connected in series with the signal detector.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1950

Patent No.	*Subject*	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,502,419	324	2,503,904[a]	360	2,505,753	76
2,502,617	308	2,503,925	224	2,505,867	140
2,502,626	228	2,503,932	68	2,505,884	444
2,502,683	308	2,504,108	16	2,505,919	308
2,502,762	80	2,504,114	16	2,506,149[a]	304
2,502,775	508, 116	2,504,118	436	2,506,157	136
2,502,863	508	2,504,119	136	2,506,341	92
2,502,938	108	2,504,454[a]	180	2,506,353	16
2,503,047	92	2,504,530	236	2,506,387	92
2,503,111[a]	490	2,504,563	520	2,506,388	92
2,503,165	168, 420	2,504,604[a]	180	2,506,419	308
2,503,247	124	2,504,611	136	2,506,431	288
2,503,298	160	2,504,644	4	2,506,433	232
2,503,302	308	2,504,719	484	2,506,435	308
2,503,304	428	2,504,772	288, 168	2,506,474	92
2,503,320	468	2,504,778	228	2,506,500	324
2,503,387	68	2,504,878[a]	304	2,506,535	168
2,503,391	372	S.N. 507,960	16	Re. 23,226[a]	304
2,503,422	444	2,504,975	316	2,506,585	200
2,503,423	444	2,504,978	104	2,506,587	32
2,503,554	464	2,505,017	316	2,506,589	484
2,503,561	80	2,505,585	436, 12	2,506,608	484
2,503,660	496	2,505,587	12, 436	2,506,609	484
2,503,676	496	2,505,599	464	2,506,624	484
2,503,730	308	2,505,601	380	2,506,648	324
2,503,831	12	2,505,636	4	2,506,818	16, 316
2,503,836	312	2,505,692	16	2,506,836	136
2,503,851	428	2,505,701	228	2,506,887	132

(a) Abstracted on preceding pages of this issue.

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2,507,222	92
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2,507,304	16
2,507,351[a]	516
2,507,367	16
2,507,385	224
2,507,439	92
2,507,451	16
2,507,567	68
2,507,636	288
2,507,652	236
2,507,695	372
2,507,708	484
2,507,746	316
2,507,770	484
2,507,776	92
2,507,854	140
2,507,863	140
2,507,900	180
2,508,081	188
2,508,098	484
2,508,163	236
2,508,290	200
2,508,349	464
2,508,350	464
2,508,384	316
2,508,400	316
2,508,419	428
2,508,451	12
2,508,456	428
2,508,485	224
2,508,494	428
2,508,544	484
2,508,565	312
2,508,571	316
2,508,572	168
2,508,623	16
2,508,677[a]	372
2,508,772[a]	304
2,508,783	484
2,508,898	16
2,508,899	520
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2,509,017	224
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2,509,208	316
2,509,210	288
2,509,224	484
2,509,230	312
2,509,327	288
2,509,344	308
2,509,345	12
2,509,389	344
2,509,394[a]	232
2,509,410	104
2,509,421	288
2,509,522	188
2,509,621	288
2,509,644	288
2,509,651[a]	356
2,509,700	308
2,509,705	344
2,509,718	68
2,509,750	316
2,509,770	200
2,509,780	224
2,509,818[a]	180
2,509,825	460
2,509,883	392
2,509,889	16
2,509,905	284
2,509,908[a]	304
2,509,968	484
2,510,018	188
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2,510,073	288
2,510,107	316
2,510,160	312
2,510,384	68
2,510,386	392
2,510,397	484
2,510,575	324
2,510,585	160
2,510,663	200
2,510,692	316
2,510,723	312
2,510,729	200
2,510,795	308
2,510,865	80
2,510,879	372
2,510,923	224
2,510,964	312
2,511,121	224
2,511,177	168
2,511,178	428
2,511,233	140, 228
2,511,408	392
2,511,508	392
2,511,564	228
2,511,599	316
2,511,649	200
2,511,663	484
2,511,664	484
2,511,665	484
2,511,669	136
2,511,689	436, 484
2,511,728	236
2,511,752	288
2,511,759	524
2,511,766	484
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2,511,831	92
2,511,855[a]	324
2,511,868	468
2,511,869[a]	180
2,511,924	68
2,511,991	92
2,512,020[a]	304
2,512,040	168
2,512,086	316
2,512,120	76
2,512,122	420
2,512,130	12
2,512,156	12
2,512,234	188
2,512,278	16
2,512,279	16
2,512,330	16
2,512,432	224
2,512,598	16
2,512,607	16
2,512,611	316
2,512,615	316
2,512,657	316
2,512,670	192
2,512,703	316
2,512,743	324
2,512,746	16
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2,512,773	308
2,512,783	92
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REVIEWS

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GEOPHYSICAL STUDIES IN THE ANTARCTIC, BY THOMAS C. POULTER

Geophysical Studies in the Antarctic, by Thomas C. Poulter. Published by Stanford Research Institute, Stanford, California, 1950, ($4.00)

This volume, printed by a photo-offset process, is a fairly detailed account of the author's geophysical work on the Second Byrd Antarctic Expedition made during 1934 and 1935. It begins with a discussion of the sound absorption characteristics of the snow and its ability to transmit acoustical energy. A description of methods of placing charges is followed by a chapter on the seismic equipment and field procedure. A five trace camera was employed, one of the traces being used for time break, one for the tuning fork circuit giving timing signals, and the other three for the detectors. The chapter on equipment and procedures drifts into a running account of the author's experiences during the first several months of operations on the ice. Sample records shown in an appendix at the back of the volume show relatively high frequency waves throughout. Good examples of multiple reflections are shown, some displaying as many as seven repetitions. A simple system for determining the depth to solid earth material is described, as well as a method of determining the dip of a reflecting bed by use of the times of the multiple reflections from its surface. Means for determining seismic velocities in ice and sea water are discussed.

The book contains several appendices; one of these is a reprint of an article published by Dr. Poulter in the Scientific Monthly of July 1939, describing in general terms the scientific work of the Second Byrd Expedition; another is devoted to a short paper describing seismic measurements on the Taku Glacier in southeastern Alaska near Juneau in the summer of 1949. The volume is replete with good photographs taken both on the Antarctic expedition and on the more recent Alaskan expedition. To some extent it is not as well organized as it might be, and some rather disturbing errors in orthography suggest a lack of careful proof reading. The use of air shooting is mentioned in the text, but receives little prominence.

C. G. DAHM

SPECIAL REVIEWS

ÜBER ANWENDUNGEN EINER FORMEL ZUR BERECHNUNG DES VERTIKAL-GRADIENTEN DER SCHWERE, BY WALTER HOFMANN

"Uber Anwendungen einer Formel zur Berechnung des Vertikal-gradienten der Schwere" (The Applications of a formula for the calculation of the Vertical Gradient of Gravity) by Walter Hofmann *Geofisica Pura e Applicata*, Milan, Italy, Vol. XIV, No. 3–4, pp. 3–20, (1949).

This paper considers the general theory of the calculation of the vertical gradient of gravity from surface integration of observed gravity anomalies on a spherical earth and its application in the interpretation of gravity data. The derivation is based on the use of spherical harmonics. The resultant final formula (Eq. 22) differs from Evjen's result[1] (which was derived on the assumption that the curvature of the earth's surface is negligible) by a constant term. The constant term is proportional to the magnitude of the gravity anomaly at the point under consideration but is very small and amounts to only 5.5 E^o for a gravity anomaly of 100 mg. Hence, Evjen's formula is sufficiently accurate in principle for all applications of practical interest in geophysical prospecting.

[1] H. M. Evjen, "The Place of the Vertical Gradient in Gravitational Interpretations," *Geophysics*, Vol. I, pp. 127–136, 1936.

The procedure for carrying out the calculations is discussed and illustrative applications are shown on maps and profiles. Of outstanding practical interest is the observation that the calculated vertical gradient associated with the very strong gravity minimum south of Java, reported by Vening-Meinesz,[2] amounts to only about 1% of the normal vertical gradient and therefore is not an important factor in the station reductions. Another application is to the gravity minimum at Lubtheen in Mecklenburg in North Germany. It is claimed that the calculated values of the vertical gradient are accurate to at most a few Eötvös units (10^{-9} c.g.s. units).

Finally, the application of the vertical gradient in the direct calculation of the interpreted causative subsurface mass as proposed by Evjen is considered in detail. The author points out that the necessary assumption that the structure may be approximated by a horizontal surface density distribution makes it impossible to estimate its depth from gravity data alone and therefore that the depth must be given by other data or considerations. With this proviso, several theoretical cases are calculated with excellent results.

SIGMUND HAMMER
Gulf Research and Development Co.

SEISMIC SOUNDING OF SHALLOW DEPTHS, BY H. HEDSTROM AND R. KOLLERT

"Seismic Sounding of Shallow Depths" by H. Hedstrom and R. Kollert, *Tellus*, vol. 1, no. 4, pp, 24–36, November, 1949.

This paper on shallow seismic prospecting begins with a long and somewhat irrelevant history of pure and applied seismology, particularly as it developed in Sweden. The body of the article describes instrumentation and techniques used in that country to measure depth to bed rock by refraction and to determine the thickness of glacier ice by reflection.

The refraction surveys have been carried on since 1941 in connection with dam site determinations. They have made possible rapid, cheap and accurate mapping of the hard-rock surface buried beneath soil, sand, glacial drift or other morainal material. These explorations, made at 75 localities all over Sweden, have yielded 4,381 depth determinations, "each one a substitute for a bore hole down to solid bed rock."

The portable seismic equipment for these surveys includes six geophones which are set along profiles at 15-foot intervals. A number of successive two to three pound shots are fired at 150 foot intervals along the profile and recorded by each geophone spread. By moving both shot and geophone setups progressively along the profile, one obtains data from which overlapping and reversed time-distance curves can be plotted. On land, a party covers only 450 feet of line per day, this requiring 25–30 shots and five to six geophone spreads. A special technique is used where the line crosses a river. The charge is dropped into the river at the desired position from a suspended cable by means of a tripping device. The geophones may be spread either on land or along the river bottom.

Data from subsequent excavations and drilling show that these refraction determinations of depth to bed rock are accurate to within ± 10 per cent for depths less than 30 feet. In one case, interval velocities were computed from elastic constants, determined in the laboratory, of samples taken from a bore hole to a depth of about 2,400 ft. The average velocity obtained from the core samples was 10,050 ft/sec., as compared with a speed of 9,740 ft/sec deduced from reflection data.

The ice measuring equipment was constructed for research on the Antarctic ice by a combined Norwegian-Swedish-British expedition to Antarctica. It was tested on a glacier in the Kebnekaise Mountains in North Sweden. The test area was such that part of the equipment had to be dropped by parachute. Reflections were obtained both with longitudinal and transverse waves. The respective velocities of these in glacier ice was 10,350 ft/sec and 4,860 ft/sec. A pronounced reverberation (multiple reflection) appeared on the best records. Ice thicknesses less than 300 feet could be measured by the reflection shooting and the authors claim that this sets a record as the shallowest reflection ever identified.

[2] F. A. Vening-Meinesz, "Gravity Expeditions at Sea," Vol. II, p. 89 ff, Netherlands Geodetic Commission, Delft, 1934.

The article clearly demonstrates the versatility and usefulness of seismic techniques in civil engineering surveys and glacial ice studies.

DART WANTLAND
U. S. Bureau of Reclamation

A DYNAMIC GRAVIMETER OF NOVEL DESIGN, BY R. L. G. GILBERT

"A Dynamic Gravimeter of Novel Design" by R. L. G. Gilbert, *Proceedings of the Physical Society of London*, Vol. 62, No. 7, pp. 445–454, (1949)

This new type of gravimeter utilizes the frequency of natural vibration of a vertical fibre stretched by a suspended weight. The idealized relation between natural frequency (F) and weight (Mg) is

$$F = 1/2L\sqrt{Mg/m}$$

where L is the length of the fibre and m is the mass of the fibre per unit length. Since L, M, and m are instrumental constants, measuring the resonant frequency F serves to determine relative values of gravity. This is accomplished by having the vibrating fibre drive an electromagnetic oscillator which is coupled with a standard frequency crystal oscillator. The integrated beat frequency is counted on dials rotated by a small selsyn motor. The principal advantages of this type of gravimeter are claimed to be (1) large range without change of precision, and (2) integration of motional accelerations. Proposed uses are in submarines in the open sea, as an underwater gravimeter, and as a borehole gravimeter.

In the first model of the instrument as described the fibre consists of a flat strip of beryllium copper about 5 cm. long. An automatic volume control system in the oscillator maintains the vibration of the fibre at a constant amplitude of about 10^{-5} cm. The suspended mass is of copper and weighs about 65 grams and is electromagnetically damped for all modes of motion. The instrument is evacuated and electrically thermostated. The natural frequency of vibration is about 1,000 cps. The time for an observation to attain a desired degree of precision depends only on the accuracy to which the phase of the wire can be measured with respect to the frequency standard. At present this is about one-tenth cycle, which yields a reading accuracy of one in 10^6 (about 2 milligals) in 100 seconds or less than two minutes. Anticipated improvement of the phase comparison to one-fiftieth cycle would yield a reading accuracy of one in 10^8 (0.02 mg.) in an observation of half-hour duration. If attainable this would permit earth tide measurements.

Laboratory and field tests on board an English submarine cruising in the English Channel are reported. A Vening-Meinesz three-pendulum apparatus was used as a standard of reference. Discarding some discordant observations which were taken under unusually rough conditions, an accuracy corresponding to a probable error of 1.5 mg. for the gravimeter alone was deduced. The author concludes that the apparatus, although only in the initial stages of development, shows great promise.

In connection with this paper it is of interest to note the following excerpt from the Annual Report for 1948–49 of the Department of Geodesy and Geophysics in the University of Cambridge (report by B. C. Browne dated October 26, 1949):

"*Dynamic Gravimeter.* Thanks to a grant from the Paul Instrument Fund of the Royal Society, considerable progress has been made in the design of this instrument and a development contract has been placed with the Cambridge Instrument Co. Ltd. Application has been made for a patent on certain novel features. Mr. Gilbert is now employed by the Anglo-Iranian Oil Company but is remaining in Cambridge to continue this work. He is developing a water tight model for use in bore holes for density measurements or for obtaining gravity measurements in shallow seas by lowering the apparatus to the bottom from a surface ship."

SIGMUND HAMMER
Gulf Research and Development Co.

JOURNAL OF THE CHINESE GEOPHYSICAL SOCIETY

Journal of the Chinese Geophysical Society, vol. 1, no. 2, June, 1949.

The first issue of this new journal was reviewed in the April, 1949 issue of *Geophysics*. Of the papers and communications in the second issue, three are meteorological, four relate to geomagnetism and atmospheric electricity, five deal with gravity and two with electrical prospecting. All but one of these are in English, the exception, on atmospheric electricity, being in French.

Three of the gravity papers are based on a survey by the Chinese Petroleum Corporation on the Island of Taiwan, where several small oil and gas fields are located. One of these is on density measurement, one on the topographic expression of subsurface anticlines revealed by the gravity data, and one on gravity results over known oil and gas structures on the island. Of more academic interest is a long paper by K. G. Ku, Y. Ceng, and C. Y. Chang, summarizing the isostatic reduction of 208 gravity stations scattered over China proper. The data were taken during the years 1934–39 with Holweck-Lejay pendulums but reduction did not commence until three years ago, when a complete set of reliable topographic maps and reduction tables was collected. Anomalies tabulated include the Free Air, Bouguer, Hayford-Bullard, Heiskanen-Airy, and Vening-Meinesz, each of the last two being specified for a number of assumed mean depths of compensation. An interpretation of the isostatic anomalies is promised for a forthcoming issue.

A paper by T. H. Chang describes the successful use of a resistivity survey to determine the depth of Quaternary gravel as an aid to drilling in the Laochunmiao oil field. Here the surface gravel contains boulders which ruin the drilling bits and cause loss of circulation. Knowledge of its depth at each well location helps in planning the drilling operations.

Dr. C. Y. Fu, the author of several important seismological papers which appeared in *Geophysics* a number of years ago, is now managing editor of the Journal.

MILTON B. DOBRIN

GEOPHYSICS

"Geophysics," *Quarterly of the Colorado School of Mines*, vol. 45, no. 4a, October, 1950. (Available from the School at $1.00 per copy.)

Early in the fall of 1949, the Colorado School of Mines celebrated its seventy-fifth anniversary by holding a series of conferences on the general topic: "Mineral Resources in World Affairs." One of the conferences was on Geophysics; six papers were delivered here and these are published in this special issue of the School's Quarterly. The program was as follows:

"The Relationship of Research and Field Operations in Seismic Explorations" by Cecil H. Green.

"Geological Imagination in the Interpretation of Geophysical Data" by R. Clare Coffin.

"Current Trends and Progress in Mining Geophysics" by Hans Lundberg.

"Recent Developments in Electrical Logging and Auxiliary Methods" by H. G. Doll and Maurice Martin.

"Recent Developments in Seismic Research" by D. H. Clewell.

"Recent Developments in Gravity Prospecting" by Sigmund Hammer.

The papers summarize current developments and present trends in a number of branches of prospecting geophysics. Being intended for a general audience, they are essentially non-technical in approach. The two papers on seismic research and that on gravity prospecting are particularly interesting because of the light they cast on current research activity which, if successful, should lead to substantial improvements in the effectiveness of the respective exploration methods.

MILTON B. DOBRIN

BEITRAG ZUR MESSUNG VON ERSCHÜTTERUNGEN, BY MAX WEBER

"*Beitrag zur Messung von Erschütterungen*" ("Contribution to Vibration Measurement") by Max Weber, *Helvetica Physica Acta*, v. 22, pp. 425–456 (1949).

This paper treats the entire subject of vibration measurement both from the theoretical and practical standpoints. The theory is quite general, being applicable to all types of transducers. Specific application of the theory is made to the piezoelectric detector and the experimental discussion deals almost entirely with this type of instrument.

In the development of the theory the displacement of the movable part of a seismometer is assumed to be linear and is studied as a function of the motion of the rigid case. The simultaneous solution of the linear equations and the transformations of variables are accomplished by means of orthogonal matrices and the result is an equation incorporating 12 transfer coefficients. This equation is apparently of academic interest only, since the author immediately goes over to the discussion of the "fundamental types," namely those for which all but one of the transfer coefficients vanish. The steady state solution for such a motion predicts that for frequencies considerably lower than the

natural frequency of the system and for zero damping, the seismometer should behave as an ideal acceleration transducer. That it does this is of course well known. For the practical case, design equations are developed giving the maximum natural frequency and damping factor with which the linear distortion and the phase shift remain within prescribed bounds for a desired upper limit of frequency. A similar study is made for frequencies considerably in excess of the natural frequency, at which the instrument becomes an amplitude transducer. No mention is made of the possibility of achieving velocity transducer operation.

As a fairly satisfactory index of non-linear distortion, the "distortion factor" is used and the seat of non-linearity is assumed to be in the spring constant. Quadratic and cubic additional terms are introduced and the equations are manipulated in such a fashion as to yield the maximum permissible acceleration amplitude for a given distortion factor.

In the discussion of piezoelectric transducer theory, equations are developed for a prismatic rod without additional mass and for a triangular rod of variable area. It is shown that such crystals may work quite satisfactorily as acceleration transducers but that they are not suitable as amplitude transducers. The equations for the prismatic rod with additional mass are also studied, the solutions being obtained by means of Stieltjes operators and the conclusion being drawn that such types are likewise suitable as acceleration transducers. A brief study is made of a differential mode of operation for two piezoelectric transducers either by biasing the rods oppositely and connecting them in series, or by biasing them in the same direction and connecting them back-to-back. This completes the highly mathematical part of the paper dealing with theoretical principles.

The rest is devoted to constructional features and experimental technique involving piezoelectric seismic transducers for a frequency range from 1–4,000 cps and a mass between 200 to 500 grams. A shaking table for calibration purposes is described. The energy is supplied by an electrodynamic generator and power amplifier capable of delivering 17 watts into the electrodynamic system. Care must be taken in its design to place the natural frequencies below and above the operating range. It is not clear from the illustration why the lower natural frequency is not kept below the indicated 30 cps.

The recording of the table's motion is accomplished by means of mechanical-optical and electro-optical amplification systems. It is surprising to find the statement that the power amplifier cannot give high-fidelity amplification of frequencies below 25 cps. It is specified that the amplitudes of the shaking table must be large compared to the average noise level.

The power developed by this type of transducer is not sufficient to drive a galvanometer and hence electrical amplification is required. A two stage push-pull amplifier with a single-ended input stage was used giving a voltage amplification of 3,000:1 and having flat frequency response from 1 cps to 4,000 cps. To realize the upper, and lower frequency limits discussed above in achieving true acceleration, and amplitude operation, the well-known RC type twin bridged-T network is used and the very interesting remark is made that when two filters with rejection frequencies f_0 and $4/5\ f_0$ are introduced into the feedback loop over one tube each, an extremely sharp high-pass filter is obtained.

Next, the possibilities of a cemented crystal "doublet" (two parallel, cemented, crystal rods or plates) are considered. If one end is clamped tight then a force acting upon the free end produces an electrostatic charge. Quartz, Ammonium and Potassium Phosphate, and Potassium Sodium Tartrate (Rochelle salt) are most commonly used. The results obtained with a triangular Rochelle salt doublet are briefly described. Impedance match is achieved by means of a subminiature electrometer tube (Raytheon) and particular attention is given to the question of correct clamping. Such a doublet, with an additional mass of 30 grams, should be useful for seismic applications since it has a sensitivity of approximately 0.06 mm/sec^2 per mm deflection, which, at a frequency of 10 cps would correspond to an earth amplitude of approximately 1.5×10^{-6} cm. The transient amplitude decay indicates that this transducer is practically undamped and hence is almost an ideal acceleration transducer, the steady state frequency response being flat from one to about 2,000 cps and the natural frequency being located in the neighborhood of 3,500 cps.

A. J. HERMONT

INVESTIGATION OF THE IRON-BEARING FORMATION OF IRON COUNTY, MICHIGAN, UTILIZING GEOPHYSICAL AND OTHER METHODS, BY PAUL ZINNER, CLYDE L. HOLMBERG, AND OWEN W. TERRY

"Investigation of the Iron-Bearing Formation of Iron County, Michigan, Utilizing Geophysical and Other Methods" by Paul Zinner, Clyde L. Holmberg, and Owen W. Terry *U. S. Bureau of Mines Report of Investigations 4583* (November, 1949) 40 p., 22 figures.

This report presents the results of comprehensive geophysical investigations and limited core drilling which were conducted during 1944–45 by the Bureau of Mines in the vicinity of Iron River, Michigan. The geophysical work, which was of primary concern, was undertaken to determine the applicability of magnetic, electrical resistivity, and gravity methods in mapping iron bearing formations and possibly in locating iron ore directly. A successful method would have unlimited value, not only in the Iron River district but throughout the Lake Superior iron-mining region, where thick glacial drift and very complex structural conditions make exploration difficult. Discoveries of new ore must now be based upon "wild-cat" drilling, extremely infrequent outcrops, or occasional magnetic anomalies associated with the ore itself.

These geophysical investigations were conducted in the Stambaugh and DeGrasse areas. The areas were selected because they were near existing mines where development and drilling permitted some geological projections as a means of interpreting the results of the contemplated geophysical work. In addition, previous geological studies had inferred the possible existence of substantial tonnages of undiscovered ore.

In the Stambaugh area, Hotchkiss Superdip readings were taken at intervals of 50 to 100 feet along grids covering an area of 250 acres. Resistivity surveys were conducted over about 60 acres in the northern part of the area that had been mapped magnetically. Observations were taken with current electrodes 2,000 ft. apart and with 50 and 100 foot separations of the potential electrodes. At seven sites in the area, an attempt was made to study the electrical characteristics by "vertical electrical drilling."

Figures are presented showing geological information, topography, Superdip profiles and contours, circuit diagrams, curves and maps based on the resistivity survey, and a single section correlating magnetic, resistivity, and geological data. A table of resistivities for samples collected from the Iron River area is included. The presentation of most of the geologic data on a separate figure makes its correlation with the geophysical data rather difficult. It appears that the iron formation which contains the ore (hematite and limonite) is generally associated with a zone of magnetic lows and highs and with resistivity highs of moderate magnitude. It is interesting to observe that the magnetic slates, which are apparently of no economic importance, give rise to the highest values both of resistivity and magnetic intensity. Interference from pipe lines, railroad tracks and power lines has complicated the magnetic and resistivity surveys and their interpretation. The failure of the resistivity-depth curves to correlate with the known depths to the pre-glacial surface was attributed to insufficient differentiation between the moisture content of the glacial drift and that of the underlying slate.

In the DeGrasse area, Superdip, resistivity, and "vertical electric drilling" surveys were conducted in essentially the same manner as those in the Stambaugh area. In addition, gravity and potential-drop-ratio surveys were conducted. The gravity survey consisted of about 250 stations situated along several lines at 10-foot and 100-foot intervals. Potential-drop-ratio surveys were made along several lines in the area with electrode separations of 25 and 100 ft. Figures are presented showing the topography, geology, Superdip profiles, observed gravity, residual gravity, and resistivity contours. In addition there is a profile comparing magnetic, resistivity, gravity, potential-drop-ratio, and geologic data. The densities of a number of rock samples from the general area and some additional rock resistivities are tabulated.

Excessive interference from pipe lines and railroad tracks required a great many stations and observations to be rejected in the magnetic and electrical resistivity surveys and prohibited geological interpretation of the potential-drop-ratio. The Superdip readings in the DeGrasse area, unlike those

in the Stambaugh area, varied so little that contouring was considered impracticable. The resistivity-depth curves, as in the Stambaugh area, failed to correlate with known depths to the pre-glacial surface. The resistivity mapping did, however, justify the location of a probable eastward projection of the footwall contact some 2,500 ft. beyond its known limits. Of particular interest is the precision of the gravity survey, which is believed to be better than 0.03 milligal. A 0.2 milligal gravity minimum is believed to be a reflection of slump in the suboutcrop of the ore body.

In summary, the geophysical investigations in Iron County, Mich. seems to have met with but limited success. Obviously, the thick glacial drift, the limited geological information, the complex geology, and the numerous interferences from railroad tracks, pipe lines and power lines have greatly complicated the interpretation. However, these comprehensive studies contribute important data and their value will undoubtedly increase as additional geologic information becomes available.

JACK W. PETERS
Magnolia Petroleum Co.

BU TSU RI TAN KO

Bu Tsu Ri Tan Ko, *Geophysical Exploration*. The Journal of the Society of Exploration Geophysicists of Japan.

In 1947 a new professional organization, the Society of Exploration Geophysicists of Japan, was organized by a group of Japanese technologists working in applied geophysics. The objectives of this society seem to be similar to those of its counterpart in the United States. Its initial convention attended by about 70 persons was held in May, 1948 at the University of Tokyo. In addition to a business meeting, at which a constitution was accepted, there were several technical papers covering exploration geophysics and allied subjects.

One of the first projects of the society was to publish a book of 100 pages summarizing developments in theoretical and applied geophysics, as well as allied subjects, from 1940 to 1947. Over 600 different projects are discussed. The information is condensed but extensive, covering exploration for metallic and non-metallic minerals, oil, natural gas, coal, well water, hot springs, and building materials. Methods considered include seismic, gravimetric, magnetic, geochemical and radioactive.

The first issue of the Society's technical journal "Bu Tsu Ri Tan Ko" (Geophysical Exploration) was published in 1948 (see Reviews Section of *Geophysics* for April, 1949). The text is entirely in Japanese. In general, the published papers are excessively condensed except for the theoretical ones, which tend to be more informative. Three papers from volume 2 (1949), numbers 1 and 2, are reviewed below. They were selected partly to illustrate the diversity of present geophysical activity in Japan.

SEISMIC PROSPECTING ON A SEA BOTTOM OVER THE COAL FIELD AT SAITOZAKI IN FUKUOKA PREFECTURE, BY S. HAENO, C. SHIRATO AND K. IIDA

"Seismic prospecting on a sea bottom over the coal field at Saitozaki in Fukuoka prefecture," by S. Haeno, C. Shirato and K. Iida. *Geophysical Exploration*, vol. 2, no. 1, pp. 24–26. Mar., 1949.

The authors present a review of the highlights of the first attempt in Japan to conduct a marine seismic exploration project. This exploration took place in the summer of 1942 on the sea bottom over a known coal field at Saitozaki. An area of approximately 16 square kilometers was covered. The average water depth was about 10 meters. The purpose of the prospect was to determine the attitude of the submarine strata to a vertical depth of about 300 meters, to locate a hidden fault, and to determine the extent and depth of the coal field.

Velocity control was secured in the shafts and tunnels of the mine. At sea a transit survey was made with weighted bamboo poles as markers. Recording and shooting equipment was carried in small boats. Six seismometer receiving points were used per spread. Interpretations were based on velocity and dip computations from records shot with reverse control. Several cross-spreads were recorded also. The authors claim very satisfactory results.

METHODS OF FINDING DEPTH AND INTENSITY OF RADON SOURCE IN RADIOACTIVE EXPLORATION, BY S. HATSUDA

"Methods of finding depth and intensity of radon source in radioactive exploration," by S. Hatsuda, *Geophysical Exploration*, vol. 2, no. 1, pp. 51–54, Mar., 1949.

Numerous papers have reported a rapid increase of radon intensity as a fault is approached, but this is claimed to be the first publication of a method for computing the depth to a fault below the weathered zone from measurements of radon concentration. In the author's method of determining the relation of radon intensity to fault depth, the following conditions are set forth: 1) the fault must penetrate the sub-surface rock strata to the sub-weathering layer; 2) the weathered zone must be of uniform thickness; and 3) absorption of radon by the sub-surface rock strata must be negligible.

The author sets up the problem as one in potential flow, using Laplace's equation in two dimensions. When boundary conditions are applied to the solution of this equation, a family of curves is obtained with radon intensity and the thickness of the weathered layer as variables from which numerical solutions can be derived. The curves show a peak concentration over the vertical axis of fault penetration with rapid fall off with lateral distance from the axis.

ON ELECTRICAL PROSPECTING FOR ANTHRACITE, BY S. YAMASHITA

"On electrical prospecting for anthracite," by S. Yamashita. *Geophysical Exploration*, vol. 2, no. 2, Sept., 1949, pp. 23–25.

The author participated in a resistivity survey for anthracite near the city of Maeda, Japan. The purpose of the survey was to determine the depth and structure of anthracite in this area. Resistivity measurements were made with a Yokogawa L-10 resistivity instrument. The Wenner system of resistivity measurements was used. The author points out the mathematical complexity of resistivity interpretations when there are more than three layers. By using suitable comparisons and assumptions, however, interpretations were made on the basis of theory developed for the four-layer case.

HENRY H. NOGAMI
Atlantic Refining Company

THE EÖTVÖS TORSION BALANCE AND THE PROBLEM OF DETERMINING THE HIGHER DERIVATIVES OF THE EXTERNAL GRAVITY POTENTIAL, BY T. OLCZAK

"The Eötvös Torsion Balance and the Problem of Determining the Higher Normal Derivatives of the External Gravity Potential" by T. Olczak, *Acta Astronomica, Cracow*, Ser C, Vol. 4, pp. 85–96 (July 15, 1949)

The first part of this paper derives the mathematical theory by which the various horizontal and vertical derivatives of the gravitational potential may be calculated from a sufficiently dense field of points of the gradient and curvature components which are observed with the Eötvös Torsion Balance. Formulas for several second-order derivatives and for all ten third-order derivatives of the gravity potential are given. Of these, two are selected as being of especial interest and are discussed in considerable detail. These are the vertical gradient of gravity ($\partial^2 w/\partial Z^2$) and the second vertical gradient (the so-called "second derivative") of gravity ($\partial^3 w/\partial Z^3$). Practical applications of the theory are illustrated by two maps of torsion balance surveys in the Subcarpathian region, together with the computed vertical gradient and second derivative. The greater detail brought out by the computed derivatives is clearly shown.

SIGMUND HAMMER
Gulf Research and Development Co.

ÜBER EIN NEUARTIGES PRINZIP DER ELEKTRISCHEN TIEFENSENDIERUNG, BY W. BUCHHEIM

"Über ein neuartiges Prinzip der elektrischen Tiefensendierung" ("On a New Principle in Electrical Prospecting) by W. Buchheim, *Geofisica Pura e Applicata*, v. 16, pp. 76–81 (1950).

A new method of electrical exploration is described in which variable currents having frequencies less than a few thousand cps are used. Two current electrodes and two potential probes are arranged so that the line connecting the probes is perpendicular to the extension of the line connecting the two electrodes. The author demonstrates that such a geometry has the unique feature that the voltage between the probes is always in phase with the current between the electrodes for the case of a homogeneous earth. Hence, voltages out of phase with the current are a direct measure of inhomogeneities in the earth. Moreover, as in all alternating current exploration methods, the effective depth of penetration decreases as the frequency increases. Hence, by plotting this out of phase voltage as a function of frequency one should obtain a fair estimate of the depth to these inhomogeneities or discontinuities.

Several advantages of this method are listed and briefly discussed. These include: 1) the direct measurement of inhomogeneities as opposed to the measurement of variations in a homogeneous earth; 2) the ease with which frequency can be varied as opposed to varying the electrode arrangements; and 3) the ability to discriminate against many types of electrical disturbances encountered in direct current exploration methods.

Some of the problems connected with suitable instrumentation for this work are mentioned. The author gives no indication as to whether this idea has been tested experimentally.

W. Jacque Yost
Magnolia Petroleum Company

PEILUNG VON BODENSCHÜTTERUNGEN FÜR TECHNISCHE ANWENDUNGEN, BY HORST KÖHLER

"Peilung von Bodenerschütterungen für Technische Anwendungen" ("Sounding with Earth Vibrations for Engineering Purposes)" by Horst Köhler, from Seismische Arbeiten, 1947–48; *Veröffentlichungen des Zentralinstitutes für Erdbebenforschung in Jena*. Akad. Verlag, Berlin, Heft 51, pp. 63–98 (1949).

This paper describes experiments conducted in Germany during World War II to investigate the possibility of locating the source of weak earth vibrations by methods analogous to those used in submarine acoustic ranging. Such vibrations, it is pointed out, might result from running machinery, traffic, tunnel construction, or mining operations. The purposes for which the proposed methods might be used are never clearly stated and, considering when the work was done, one might speculate on possible military applications. The paper has little direct connection with seismic prospecting but some conclusions are reached on the directional characteristics of seismic waves and detecting instruments which might be applicable to exploration problems.

Piezo-electric accelerometers were employed in the field tests, which were conducted at two locations, one chosen for the homogeneity of the near-surface geology, the other chosen because of its inhomogeneity. A shaking machine was used to generate continuous-wave earth vibrations having a variable frequency, while falling weights were employed to obtain low amplitude reproducible shock waves similar to those generated by explosions. Transmission both along the surface and at ten meter depths was studied. The horizontal detector employed showed a definite directional response but the characteristic plot showed little relation between the direction of maximum detector output and the bearing of the source. At one frequency the maximum might be in the direction of the source while at another it would be observed when the instruments axis was perpendicular to the line from the source. This behavior is explained by the fact that simultaneously arriving transverse and longitudinal waves give rise to an elliptical ground motion which has a principal axis whose direction varies with frequency.

Groups of detectors were employed to test the feasibility of sounding by "sum and difference" methods used in underwater acoustic location. At one test site the directionality pattern obtained in this manner showed a pronounced maximum pointing directly to the source. Repetition of the experiment at a location only 100 meters away gave two maximum lobes, the larger pointing 30° away from the source. Theoretical analysis shows how the phase difference between waves reaching two detectors from the same source depends on the near-surface geologic structure in addition to the direction of the source, thus explaining the failure of the method.

It was found that a number of detector pairs along a line could locate the source at the intersection of the hyperbolae corresponding to the measured time differences. This method was valid only for impulsive sources close enough to the detectors to give clear-cut first arrivals. Intensity measurements along several profiles could locate a position of maximum amplitude along each profile and the source should be at the intersection of perpendiculars to the profiles at each position. This method appeared feasible only within 60–100 meters of the source.

In seismic exploration the direction from which reflected waves approach is best indicated by step-out times on traces representing successive detector units along a profile. This procedure should be applicable to establishing the direction of horizontal wave travel but it is not mentioned by the author. It is felt that the effect of surface waves on the directional characteristics is not taken sufficiently into account.

MILTON B. DOBRIN

ECONOMIC MINERAL DEPOSITS, BY ALAN M. BATEMAN

Economic Mineral Deposits, 2nd Edition by Alan M. Bateman, John Wiley & Sons, N. Y. (1950).

This is a treatment of mineral deposits that will appeal especially to those associated with and active in exploration who, nevertheless, are not professional geologists. The approach is direct and factual, and the scope broad, with an excellent and logical division of subject matter. Numerous careful tables and listings provide rapid useful reference, and are to be commended for making the text more readily assimilable. Of necessity, much of the material is in summarized form; nevertheless, controversial points are indicated. The numerous diagrams and illustrations are frequently reduced to an outlining statement. This permits the assemblage and covering of a vast amount of material in condensed but readable form. The book is the type of broad reference text to which the student or engineer may well go for a generalized picture and for direction as to source material. The professional geologist on the other hand may demand more detailed treatment that could scarcely be incorporated.

The first part of the book deals with the principles and processes by which mineral deposits come into being. An interesting history is followed by a discussion of various ways in which ore deposits may arise and the localizing controls exercised. Interesting points to the reviewer were the tabulation on geologic thermometers, the discussion of mineral concentrations and enrichment, the listing of igneous rocks and associated minerals and the outline of metallogenetic epochs and provinces.

In the second part, the metallic deposits are discussed and referred to the classifications and controls already set forth. The precious metals, the base metals, and the iron and ferroalloy metals are considered, each with respect to geographic location of the chief known deposits. This part closes with an outline on the minor metals and related nonmetals, of interest due to the increasing economic importance of such occurrences.

The third and last part of the book covers the non-metallic mineral deposits, including fuels, ceramic, structural, refractory, industrial, chemical, fertilizer and abrasive materials, and gemstones. Mention is also made of the principles governing the collection and location of ground water supplies. This part of the book covers a section of mineral deposits of growing industrial value. Its presence and consideration within the scope of this text adds greatly to its breadth and application as a comprehensive summarized treatment of economic mineral deposits.

A. A. BRANT

PUBLICATIONS RECEIVED

Listed below are all publications received at the business office of the society on subscription and through free exchange for *Geophysics* since publication of the last issue. Periodicals and separates indicated by the asterisk (*) have been forwarded to the Special Reviews Committee, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications will be held for a short time at the business office. Disposition of books listed is made by the Special Reviews Committee.

Periodicals

American Journal of Science, Vol. 248, Nos. 6, 7 and 8 (June–Aug., 1950)
**Annales de Geophysique*, Vol. 6, No. 1 (Supplement) and No. 2 (Jan.–June, 1950)
**Boletin de la Asociacion Mexicana de Geologis Petroleros*, Vol. 2, Nos. 2, 3, and 4 (Feb.–Apr., 1950)
Bulletin of the American Association of Petroleum Geologists, The, Vol. 34, Nos. 5, 6, 7 & 8 (May–Aug., 1950)
**Bulletin of the Hungarian Geological Society*, Vol. 80, Nos. 1–3 and 4–6 (1950)
**Bulletin of the Seismological Society of America*, Vol. 40, No. 2 (April, 1950)
**Canadian Geophysical Bulletin*, Vol. 3, No. 4 (1949) and Vol. 4, No. 1 (1950)
Economic Geology, Vol. 45, Nos. 3, 4 & 5 (May–Aug., 1950)
**Erdöl und Kohle*, Vol. 3, Nos. 4, 5, 6 & 7 (Apr.–Jul., 1950)
**Geofisica Pura e Applicata*, Vol. 16, Nos. 1–2 (Jan.–Mar., 1950)
Institute of Petroleum Review, Vol. 4, Nos. 41, 42 & 43 (May–Jul., 1950)
Instruments, Vol. 23, Nos. 7 & 8 (Jul.–Aug., 1950)
Journal of Applied Physics, Vol. 21, Nos. 5, 6, 7 & 8 (May–Aug., 1950)
Journal of Geophysical Research, Vol. 55, No. 2 (June, 1950)
Journal of the Institute of Petroleum, Vol. 36, Nos. 317 & 318 (May–June, 1950)
**LEA*, Union Panamericana, Vol. 10, No. 12 (Dec. 1949), Vol. 11, No. 1 (Jan, 1950)
**Nafta*, Vol. 6, Nos. 3, 4, 5 & 6 (Mar.–June, 1950)
**Nuclear Science Abstracts*, Vol. 4, Nos. 9 through 15 (May 15–Aug. 15, 1950)
Physics Today, Vol. 3, Nos. 6 & 7 (Jun.–Jul., 1950)
**Proceedings of the Cambridge Philosophical Society*, Vol. 46, Nos. 1 and 3 (Jan. & July, 1950)
**Quarterly Journal of the Geological Society of London*, Vol. 105, No. 2 (Mar., 1950)
Review of Scientific Instruments, Vol. 21, Nos. 5, 6 & 7 (May–July, 1950)
**Revista Geomineraria*, Vol. 11, No. 1 (1950)
**Annales de la Societe Geologique de Pologne*, Vol. 18 (1948) and Vol. 19 (1949)
**Tellus*, Vol. 2, No. 1 (Feb., 1950)

Separates

"Bodenkundliche Übersichtskarte von Nordrhein-Westfalen, Blatt Dusseldorf/Köln," Amt fur Bodenforschung, Celle, Germany
"Geologische Karte des rheinisch-westfalischen Steinkohlengebietes, I. Lieferung," Amt fur Bodenforschung, Celle, Germany
"Geologishe Übersichtskarte von Deutschland, Blatt Detmold und Minden," Amt fur Bodenforschung, Celle, Germany
"Geologisches Jahrbuch für 1943–1948, Band 64," Amt fur Bodenforschung, Celle, Germany
"Gravimetermessungen uber der jungen Vulkanzone Islands," A. Schleusener
"Grundlagen der Grofbregionalen Gravimetermessungen fur das Amt fur Bodenforschung," A. Schleusener

Books

Earth for the Layman, The (June, 1950), Report No. 2, American Geological Institute
Geological Guide Books and Road Logs in the United States, Report No. 4, American Geological Institute
Prospection Geophysique, Vol. I (1950), Edmond Rothé and J. P. Rothé

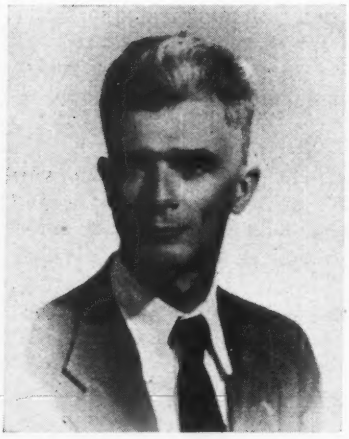
CONTRIBUTORS

J. A. BROOKS, JR., attended Rice Institute and in 1927 received the B.S. Degree in geology from Colgate University. In 1928 he was employed as a member of a refraction seismograph crew by Gulf Production Company. He has been with the geophysics department of Humble Oil and Refining Company since 1930 in domestic and foreign service, except for military leave from 1942 to 1944 while in the U. S. Navy. He is now supervisory computer for Humble.

J. A. BROOKS, JR.

KENNETH L. COOK

KENNETH L. COOK received his B.S. degree in physics in 1939 from the Massachusetts Institute of Technology. During the next four years he continued his studies in geology and physics at the University of Chicago, at the same time engaging in part-time teaching duties as a University Fellow and, during his last two years of attendance, as instructor. In 1943 he received his Ph.D. degree in geology and physics from the University of Chicago. Since that time he has been actively engaged in geophysical field work as geophysicist in the Division of Geophysical Exploration of the U. S. Bureau of Mines (1943–1946) and in the Geophysics Branch of the U. S. Geological Survey (1946 to present). This field work has comprised chiefly strategic-mineral investigations in mining districts of the West for iron, copper, lead, zinc and salt, in which he has employed magnetic, gravitational, electrical (surface and well-logging), and refraction seismic surveys as guides in the exploration. He has also made regional gravity surveys in eastern Maryland, northeastern Oklahoma and southeastern Kansas. He is a member of Sigma Xi, American Geophysical Union, American Institute of Mining and Metallurgical Engineers and Society of Exploration Geophysicists.



GABOR DESSAU

GABOR DESSAU studied at the Universities of Pisa and Rome and from the latter he received his Ph.D. in Mining Engineering in 1929. During 1932 and 1933 he was in the service of the Italian Bureau of Mines in Sicily. From then until 1937 he was Assistant to the Chair of Mines at the Engineering School of Turin. In February 1938 he went to Addis Ababa as head of the Geophysics and Mining Geology Section of the General Mining Inspectorate for Italian East Africa. In July 1945 he joined the Geological Survey of India. In 1948 he returned to Italy with the Colonial Ministry and was assigned to the Italian Geological Survey. He has recently carried out magnetic and electrical investigations for ores, and a detailed geological study of an antimony-bearing area in Central Italy. He is a member of the Society of Exploration Geophysicists.

VERNON L. REDDING was graduated from Colorado School of Mines in 1940 with a degree in Geological Engineering. After serving as Captain in the U. S. Army Air Corps from 1941 to 1945, he entered the University of Denver, from which he received the M.S. degree in Physics in 1947. He has served as Geologist for Continental Oil Company, worked for General Electric Company at the Hanford Works in Washington and, since July, 1949, he has been with Humble Oil & Refining Company in geophysics research.

VERNON L. REDDING

NEAL J. SMITH

NEAL J. SMITH received his B.A. and M.A. degrees, both in Geological Sciences, from the University of California in 1934 and 1936, respectively. Except for a few months in early 1936 with the Shell Oil Company, he has been in the employ of either The California Company, or The Standard Oil Company of Texas, as a coordinator of various types of geophysical prospecting, and as an interpreter of the data with particular reference to gravity and seismic methods. In the spring of 1945 he was placed in charge of the Geophysical Division of The California Company in which position he remained until incapacitated by a serious illness in late 1947. He is currently acting as Geophysical Consultant for The California Company. He is a member of the American Association of Petroleum Geologists, and the Society of Exploration Geophysicists.

S. S. WEST

S. S. WEST received his B.S. in 1930 and his Ph.D. in 1934, both from the California Institute of Technology. During 1934–1936, he was research assistant to Dr. A. L. Hughes at Washington University in St. Louis, where he conducted research on the scattering of electrons in gases. From 1936 to 1938, he was chief physicist for Subterrex in Houston, Texas, where he directed the development of methods of electrical prospecting. From 1938 to 1945, he was employed in the Tulsa laboratory of the Stanolind Oil and Gas Co. to investigate problems in the fields of seismic, electrical and soil-gas prospecting. Three years of that time were spent on the construction and use of a mass-spectrometer for the analysis of hydrocarbon mixtures and the measurement of the relative abundance of the carbon isotopes in natural sources.

In 1945, Dr. West went to Alaska, where he was assistant professor of physics at the University of Alaska until 1948, and chief of the upper atmosphere physics section of the university's Geophysical Institute for the following year. In the latter position he directed research on the determination of the temperature of the upper atmosphere from ionospheric measurements and from the scatterings of light from a searchlight beam, and on the measurement of ozone concentration as a function of height. During the fall and winter of 1949–1950, he worked on seismological problems in the exploration of Naval Petroleum Reserve No. 4 on the Arctic coast, and since then he has been carrying on research on tectonics and seismology in connection with the Geophysical Institute.

Dr. West is a member of the American Anthropological Association, the American Association for the Advancement of Science, the Society for Applied Anthropology, and the Society of Exploration Geophysicists.

In addition, references are cited to earlier issues for the biographies of: Arnaldo Belluigi, Francis F. Campbell and Sigmund Hammer, Vol. XIV, No. 4 (October, 1949); M. M. Slotnick, Vol. XV, No. 2 (April, 1950).

SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualification of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

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William Henry Luehrmann (H. F. Dunlap, L. P. Whorton, J. L. Martin)
Terence O'Brien (N. Frost, I. J. Bourne, J. C. Templeton)
John Chapman Parker (Byron K. Johnson, C. E. Myers, G. M. Mace, Jr.)
Douglas Herbert Parry (Bruce McDougall, C. J. Chapman)
Jack Michael Pierce (John D. LaTouche, Mark Whelan)
Gerald Fay Pirsig (Frank Goldstone, John Nash, Sherwood Buckstaff)
James Neal Reeves (O. T. Lawhorn, U. A. Rowe, A. C. Yokubaitis)
R. Burton Rose (Opie Dimmick, David R. Weichert, W. B. Sibley)
Thomas Adams Roy (R. W. Shoemaker, D. H. Scott, N. J. Lea)
Oscar Schneider (Matthew T. Murray)
Edwin Forrest Smith, Jr. (Robert N. Bills, Clayton N. Winn, K. M. Lawrence)
Robert Wilson Solomon (J. W. Bolinger, A. G. Starr, S. A. Teasley)
Billie Alfred Toliver (K. G. McCann, Laurence G. Cowles, James H. Rucker)
Vladimir S. Tuman (R. Davies, L. H. Tarrant, J. McG. Bruckshaw)
Keeva Vozoff (B. F. Howell, Jr., A. O. C. Nier)
Donald James Walker (S. G. Pearson, L. I. Brockway, R. J. Copeland)
Harry Bernard Walz (E. M. Wolters, S. A. Spencer, Fred Forward)
Salvador Ferradas Wessel (Matthew Murray)

TRANSFERS TO ACTIVE

Frank M. Cowell, Jr.
Otto Koefoed
Robert L. Kretz
Samuel T. Martner
George N. Meade
Lynn Alton Smitherman
Tom Fleming Southgate
Paul Ladell Walton

TRANSFERS TO ASSOCIATE

C. W. Bowlby
William J. Cunningham
James R. Engelhardt
Henry M. Hobart, Jr.
David Franklin Jewell Jr.
John R. Reese

REINSTATEMENT TO ACTIVE

James Welch Gary

NOMINEES FOR 1951–52 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented to acquaint members of the society with nominees appearing on the official ballot which will be mailed to all voting members at a later date.

FOR PRESIDENT

SIGMUND HAMMER

SIDON HARRIS

SIGMUND HAMMER was born August 13, 1901, in Webster, South Dakota, where his father was for many years a Norwegian-Lutheran Minister. He received the B.A. degree at St. Olaf College, Northfield, Minnesota, in 1924. As a student assistant in the physics department there he participated in the design, construction, and operation of the college broadcasting station, WCAL, which is still in operation. From 1924 until 1929 he was teaching fellow and graduate student in the physics department at the University of Minnesota where he received the Ph.D. degree (major: Physics; minor: Mathematics). During this period, summers were spent in employment as radio operator on board ship, research assistant and radium technician in the University Hospital.

Dr. Hammer has been employed in the gravity interpretation section of the geophysics division of the Gulf Research & Development Company, Pittsburgh, Pennsylvania, since 1929, and has had charge of the section since 1946. He also is a lecturer in geology at the University of Pittsburgh, where he teaches a course in geophysical prospecting. He has published several technical papers on the gravitational field of the earth, geophysical prospecting, and geophysical applications of the statistical theory of errors.

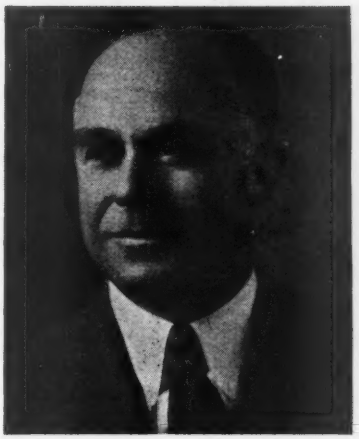
Dr. Hammer is a member of the American Physical Society, Physical Society of Pittsburgh (secretary-treasurer in 1941, vice president in 1942 and president in 1943), American Association for the Advancement of Science, Pennsylvania Academy of Science, Sigma Xi, American Association of Petroleum Geologists, American Geophysical Union (member, Special Committee on the Geophysical and Geological Study of the Continents) and Society of Exploration Geophysicists (chairman, Regional Program Committee for the Eastern Region; general chairman for the Eastern Regional Meeting in Pittsburgh, 1947). At present he is vice president of the society.

SIDON HARRIS was born in Austin, Texas, on August 28, 1908, and received his elementary education in the Austin public schools. He received his B.A. degree from the University of Texas in June, 1929, and his M.A. from the same institution in August, 1929 (major: physics; minor, electrical engineering and mathematics). He entered the field of geophysics in September, 1929, as a computer for the Humble Oil and Refining Company and resigned this job in September, 1930, to accept a

fellowship at Rice Institute where he remained as a teaching fellow until June, 1932. At this time he accepted a tutorship in the physics department at the University of Texas, where he remained until completing his doctorate in June, 1934 (major: physics; minor: mathematics). After a brief stay on the faculty of Oklahoma A & M College, he accepted a position as party chief with the Western Geophysical Company in December, 1934, was made supervisor in 1937, and was transferred to Stanolind Oil and Gas Company geophysical department early in 1938. In 1940 he was promoted to division seismograph supervisor, which position he held until resigning in November, 1944. After a few months as a consulting geophysicist, he was named president of Southern Geophysical Company, which position he now holds.

Mr. Harris has published numerous articles in scientific and trade journals in this country and abroad, including several articles in *Geophysics*. He is a member of Phi Beta Kappa, Sigma Xi, Society of Exploration Geophysicists, The American Association of Petroleum Geologists, American Physical Society and the American Geophysical Union. He is a past president of the Fort Worth Geophysical Society and is at present serving on the Standing Committee on Honors and Awards of the Society of Exploration Geophysicists.

FOR VICE PRESIDENT



CURTIS H. JOHNSON

W. W. NEWTON

CURTIS H. JOHNSON was graduated from the University of California at Los Angeles in 1932 with an A.B. and Honors in Physics, and took postgraduate work in acoustics, also at U.C.L.A. From 1933 to 1938 he was geophysicist and later chief geophysicist with Rieber Laboratory. From 1939 to the present date he has been employed by General Petroleum Corporation where he currently holds the position of senior geophysicist.

Mr. Johnson is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists and the American Geophysical Union. He has served the S.E.G. as vice chairman of the Arrangements Committee for the national convention in Los Angeles in 1947, chairman of the Program and Arrangements Committee for the 1947 Pacific Coast Regional Meeting and chairman of the Pacific Coast Program Committee for the 1948 annual meeting. In 1948 he participated in the organization of the Pacific Coast Section of the Society of Exploration Geophysicists and was elected its first president.

His recent activities on behalf of the society include membership on the Standing Committee on Honors and Awards, 1949–50 and 1950–51, and a current appointment as member-at-large on the Standing Committee on Program and Arrangements for the 1951 annual meeting.

WILLIAM W. "IKE" NEWTON received his B.A. and B.S. degrees in Mathematics in 1928 from Trinity University, Waxahachie, Texas. He was employed by the Geophysical Research Corporation from 1928 to 1930 as computer and observer on a seismograph crew. From 1930 to 1931 he was employed as an observer by Geophysical Service Inc. In 1931 and 1932 he attended Massachusetts Institute of Technology, doing graduate work in electrical engineering. From 1932 to 1936 he was employed by Geophysical Service Inc., Dallas, Texas, as party chief of a seismic party. Since 1936 he has been employed by The Geotechnical Corporation and, at the present time, is president of the Geotechnical Corporation of Delaware.

He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, past president of the Dallas Geophysical Society, member of the American Geophysical Union, Institute of Radio Engineers and the American Institute of Mining and Metallurgical Engineers.

FOR SECRETARY-TREASURER

E. D. ALCOCK

R. C. DUNLAP, JR.

E. D. ALCOCK received an A.B. degree in Mathematics from the University of California in Los Angeles in 1930 after which he was employed by the Bell Telephone Laboratories for two years as a research engineer. He then returned to obtain his Ph.D. degree in physics at the California Institute of Technology, in 1935.

Upon completion of graduate work, Dr. Alcock entered the geophysical industry as seismologist with the Shell Petroleum Corporation, a position he held for three years. He then joined National Geophysical Company, Inc., and is now vice president.

ROBERT C. DUNLAP, JR., was graduated from Southern Methodist University in 1933 with a B.S. and Honors in Geology, and took postgraduate work in geology and geophysics at Harvard University in 1933–1934.

In July, 1934 he was employed by Geophysical Service Inc. as a computer and was promoted to party chief in 1937. In 1943 he became a field supervisor and in 1949 was made vice president in charge of the pacific coast division of the company. He has worked in the Gulf Coast, Mid-Continent, Rocky Mountain and Pacific Coast areas.

Mr. Dunlap is a member of the Society of Exploration Geophysicists and The American Association of Petroleum Geologists. He has served the S.E.G. as secretary-treasurer of the Pacific Coast Section in 1947–1948, president of the Pacific Coast Section in 1948–1949 and a member of the Standing Committee on Distinguished Lectures in 1949–1950.

FOR EDITOR

MILTON B. DOBRIN

MILTON B. DOBRIN received the B.S. degree in Physics at the Massachusetts Institute of Technology in 1936, the M.S. in Physics at the University of Pittsburgh in 1941, and the Ph.D. in Geology (with specialization in geophysics) at Columbia University in 1950. From 1937 to 1942 he was employed by the Gulf Research and Development Company at Pittsburgh and in Oklahoma working on the interpretation of seismic reflection and refraction data and on the development of interpretation methods. In May, 1942 he joined the staff of the Naval Ordnance Laboratory in Washington, where he became head of an analysis section in underwater acoustics. While at NOL he initiated, planned, and participated in an underwater seismic refraction survey of Bikini atoll carried on in connection with the 1946 atomic bomb tests.

In 1947 Dr. Dobrin resumed his graduate work under Professor Maurice Ewing at Columbia University. In 1948 he became Lecturer in Geology at Columbia, organizing and teaching two new geophysics courses. He is now completing revision of his lecture notes for one of the courses into a book, "Introduction to Geophysical Prospecting" to be published by McGraw-Hill in 1951. In the summer of 1948 he inaugurated a research program in ice resistivity, telluric currents, and microseisms at the Arctic Research Laboratory, Point Barrow, Alaska.

Since September, 1949, Dr. Dobrin has been at the Magnolia Petroleum Company's Field Research Laboratories in Dallas as Senior Research Physicist. He is now engaged in fundamental studies on seismic waves.

Dr. Dobrin is the author of scientific papers covering such subjects as geological models, salt dome mechanics, seismic interpretation, the Bikini refraction survey, underwater noise measurements, and seismic surface waves. He is a member of the American Physical Society, the American Geophysical Union, Geological Society of America, American Association for the Advancement of Science, the Dallas Geophysical Society (for which he is Chairman of the Projects Committee) and the Society of Exploration Geophysicists. He has served on four S.E.G. committees and at present, as Chairman of the Special Reviews Committee, edits the reviews section of *Geophysics*.

PAUL L. LYONS

PAUL L. LYONS received his A.B. degree in geology from DePauw University in 1933 and completed work on his M.Sc. in geology from Tulsa University in 1942. He began work in geophysics on a Humble Oil and Refining Company seismograph party in 1934. In 1935 he was transferred to The Carter Oil Company in Tulsa as a computer. In 1943 he became chief computer and in 1947 technical geophysical supervisor for Carter. In 1949 he became technical assistant to the vice-president in charge of exploration. In 1950 he became staff geologist in Tulsa for Carter's eastern division. In 1948 he served as vice-chairman of the Public Relations Committee of S.E.G. and as chairman of the committee in 1949. He is currently chairman of the same committee and vice-chairman of the Program and Arrangements Committee. He is a member of the American Association of Petroleum Geologists, the Tulsa Geological Society, and the Geophysical Society of Tulsa. He is at present first vice-president of the Tulsa section.

OFFICERS OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

Year	*President*	*Vice-President*	*Secretary-Treasurer*	*Editor*
1930–31	Donald C. Barton	E. E. Rosaire	John F. Weinzierl	
1931–32	Donald C. Barton	G. H. Westby	John F. Weinzierl	Paul Weaver
1932–33	Paul Weaver	G. H. Westby	John F. Weinzierl	L. W. Blau
1933–34	Eugene McDermott	J. P. Schumacher	John F. Weinzierl	L. W. Blau
1934–35	E. E. Rosaire	F. Goldstone	Bela Hubbard	B. B. Weatherby
1935–36	B. B. Weatherby	L. W. Blau	G. H. Westby	F. M. Kannenstine
1936–37	L. W. Blau	G. H. Westby	John H. Wilson	F. M. Kannenstine
1937–38	J. C. Karcher	F. M. Kannenstine	M. E. Stiles	M. M. Slotnick
1938–39	F. M. Kannenstine	W. T. Born	H. B. Peacock	M. M. Slotnick
1939–40	E. A. Eckhardt	W. T. Born	John H. Crowell	R. D. Wyckoff
1940–41	W. T. Born	H. B. Peacock	Andrew Gilmour	R. D. Wyckoff
1941–42	H. B. Peacock	F. Goldstone	W. M. Rust, Jr.	R. D. Wyckoff
1942–43	F. Goldstone	R. D. Wyckoff	T. I. Harkins	Joseph A. Sharpe
1943–44	R. D. Wyckoff	W. M. Rust, Jr.	Hart Brown	Joseph A. Sharpe
1944–45	W. M. Rust, Jr.	Henry C. Cortes	W. Harlan Taylor	Joseph A. Sharpe
1945–46	Henry C. Cortes	J. J. Jakosky	Cecil H. Green	L. L. Nettleton
1946–47	J. J. Jakosky	Cecil H. Green	Geo. E. Wagoner	L. L. Nettleton
1947–48	Cecil H. Green	L. L. Nettleton	T. A. Manhart	M. King Hubbert
1948–49	L. L. Nettleton	Andrew Gilmour	E. V. McCollum	M. King Hubbert
1949–50	Andrew Gilmour	George E. Wagoner	Kenneth E. Burg	Richard A. Geyer
1950–51	George E. Wagoner	Sigmund Hammer	Francis F. Campbell	Richard A. Geyer

CONTEST FOR DESIGN OF THE SOCIETY CREST

Members of all grades in the Society of Exploration Geophysicists are invited to compete in a contest to obtain the design of an official crest symbolizing the science of exploration geophysics. First prize will be a paid life membership in the society, including subscription to the society's journal. Following are the rules of the contest.

1. Entries, to qualify, must be received at the office of the society, 1138 E. 37th St., Box 7248, Tulsa 18, Oklahoma, on or before March 1, 1951. Only active, associate or student members in good standing of the Society of Exploration Geophysicists shall be eligible to enter.

2. Line drawings must be made with india ink on plain white paper or on tracing cloth. Lettering, if used, must be of sufficient size to be legible after reduction. Designs shall be judged on simplicity and clarity of meaning. They may be of any geometric form considered practical for use in the embellishment of award certificates, plaques, corporate seal or society letterhead. As a guide to the general nature of suitable designs, your attention is invited to the official crests of other societies, such as Geological Society of America, American Geophysical Union, American Institute of Metallurgical Engineers, Houston Geological Society, etc., or to the designs used by some of the geophysical companies whose advertisements appear in *Geophysics*.

3. The Standing Committee on Honors and Awards shall be the sole judges. All entries shall become the property of the Society of Exploration Geophysicists and cannot be returned to contestants.

4. Announcement of the results will be made at the 1951 annual meeting.

Standing Committee on Honors and Awards

THIRD WORLD PETROLEUM CONGRESS

The National Committee for the USA for the Third World Petroleum Congress Meeting in The Hague on May 28–June 6, 1951 has completed its organization as follows:

E. V. Murphree, Standard Oil Development Company, N. Y.—*Chairman*
F. S. Clulow, Shell Oil Company, New York—*Vice-Chairman*
Paul D. Foote, Gulf Research & Development Co., Pittsburgh—*Vice-Chairman*
K. G. Mackenzie, The Texas Company, New York—*Secretary*

The Membership of the Executive Committee is as follows:

Earl Bartholomew, Ethyl Corporation, Detroit
W. F. Faragher, Houdry Process Corporation, Philadelphia
and the officers

The membership of the Committee at the present time is as follows:

R. C. Alden, Phillips Petroleum Company, Bartlesville, Oklahoma
A. H. Bell, Natural Resources Building, Urbana, Illinois
Earl Bartholomew, Ethyl Corporation, Detroit, Michigan
J. E. Brantly, Drilling & Exploration Co., Inc., Abilene, Texas
F. S. Clulow, Shell Oil Company, New York, New York
W. F. Faragher, Houdry Process Corporation, Philadelphia, Pennsylvania
Paul D. Foote, Gulf Research & Development Co., Pittsburgh, Pennsylvania
A. P. Frame, Cities Service Research & Development Co., New York, New York
J. R. Keith, California Texas Oil Company, Ltd., New York, New York
C. G. Kirkbride, Houdry Process Corporation, Philadelphia, Pennsylvania
E. V. Murphree, Standard Oil Development Company, New York, New York
K. G. Mackenzie, The Texas Company, New York, New York
L. L. Nettleton, Gravity Meter Exploration Company, Houston, Texas
C. E. Reistle, Jr., Humble Oil & Refining Company, Houston, Texas
J. K. Roberts, Standard Oil Company (Indiana), Chicago, Illinois
M. E. Spaght, Shell Development Company, Inc., San Francisco, California
H. G. Vesper, California Research Corporation, San Francisco, California

The Executive Committee has established the following procedure in the handling of papers from the United States of America:

1. In the case of papers already offered direct to the officers of the Congress in The Hague, title of each paper, the author or authors, and a brief synopsis should be sent immediately to the Secretary of the United States Committee, K. G. Mackenzie.
2. If manuscripts have already been submitted directly to the officers at The Hague, title of paper, the authors and, if possible, a brief synopsis should be sent to K. G. Mackenzie.
3. In the case of papers not already prepared and sent, an original and two copies should be sent to Mr. Mackenzie not later than October 1, 1950, so that the papers may be promptly processed and transmitted to the officers of the Congress in The Hague prior to their deadline of November 1, 1950.
4. Where papers have not already been offered, either directly to The Hague or to members of the National Committee for the USA, Mr. Mackenzie should be advised immediately of the title of the paper, the authors, and be given a brief synopsis. The Secretary of the National Committee for the USA will be glad to supply to anyone interested, the List of the Master Sections of the Congress together with certain prepared Suggestions to Authors.

The presentation of a paper does not require the personal attendance of the author at the Congress. Where an author cannot be present, the officers of the Congress will arrange for a reader. Consequently, Mr. Mackenzie should be informed as early as possible of all papers where a professional reader will have to be supplied.

Where the author or authors will personally present the paper, Mr. Mackenzie should be informed so that the program can be completed promptly.

ASSIGNMENT OF GEOLOGISTS AND GEOPHYSICISTS WHO ENLIST OR ARE DRAFTED INTO THE ARMY

Analysis of the use of technically trained personnel of the Armed Services during World War II revealed that those who entered the service as enlisted men had the least chance of using their technical training or experience. Trained manpower for technical jobs became so scarce because of

diversion into non-technical duties that the Army finally established a "Technical Detachment." Between 1945 and 1947 this method of screening sorted out about 2,000 young men with the bachelor degree in one of the physical sciences and engineering and assigned them, at least initially, to technical activities. When the peacetime draft was initiated in 1948, a new Technical Detachment was established and approximately 500 men have been assigned under this regulation. The Director of one of the Army technical laboratories recently stated that the men assigned to his laboratory under this procedure had saved several important programs. Of course assignment of this type probably will prevent attendance at Officers Candidate School but for those individuals for whom there is no space in O.C.S., assignment through this special regulation will insure at least some use of technical competence and training.

Following is a summary of Army Special Regulation Number 615-205-1, 8 December 1948. The purpose is to immediately identify and automatically assign technical personnel for "evaluation and determination of assignment, regardless of location, quotas or ordinary mental-physical and assignment instructions." The circular defines specialized and professional personnel as individuals whose occupation and military background training and/or education has equipped them for duties in scientific or technical activities, on research and development projects, or other professional types of service.

The *minimum* qualifications stated are:

a. Three full years of college; an A.G.T. (intelligence) score of not less than 130; a major in one of the physical, biological or social sciences; or
b. Completion of two full years in an accredited school of engineering etc. and an A.G.T. score of not less than 110.

This automatically includes individuals with a bachelor or higher degree in one of the sciences or fields of engineering. The minimum requirements for a student of geology (which would include geophysicists, although this is not specifically stated) are as follows: "must have completed a minimum of 14 semester hours or 21 quarter hours in a geology major, including advanced courses involving field and laboratory work."

Assignment is made after completion of basic training. Students in geology, or others with the required qualifications for special assignment under Special Regulation 615-205-1, if not tagged under this circular, should bring it to the attention of the appropriate authorities immediately following their induction or enlistment. *If no action is taken,* they should send their name, rank, serial number and name of the organization to which they are assigned to: American Geological Institute, 2101 Constitution Ave., N.W., Washington 25, D. C., and this information will be brought to the proper authorities in the Army.

As far as is known, no similar mechanism for the special allocation of enlisted or drafted specialists has been established by either the Navy or the Air Force.

—A.G.I. Newsletter

ROSTER OF GEOLOGISTS AND GEOPHYSICISTS WITH MILITARY EXPERIENCE

The Committee on National Responsibilities of Geologists, A.A.P.G., has sponsored the compilation of the military records and/or Reserve affiliations of geologists who are members of the Association. This now numbers more than 1,800 and copies of each questionnaire have been deposited in Institute headquarters. It is anticipated that this roster will be utilized by government agencies and the Defense Department in approaching individuals with specific talents and experience for the performance of specific tasks. Key officials at all levels in government will be notified of the existence and location of this roster.

Since other geological and geophysical societies have not prepared such a roster, it is requested that all geologists and geophysicists with military experience who are not members of the A.A.P.G. please communicate with Institute headquarters immediately. A penny postal card will bring you a form by return mail.

—A.G.I. Newsletter

FORT WORTH REGIONAL EXPLORATION MEETING

The Fort Worth Geophysical Society, Fort Worth Geological Society, Dallas, Ark-La-Tex, Tulsa and Permian Basin Geophysical Societies will sponsor a regional exploration meeting to be held at the Texas Hotel in Fort Worth, Texas, Thursday and Friday, November 30 and December 1, 1950. There will be no charge for registration which will commence Wednesday evening, November 29.

Immediately following the opening of the meeting on Thursday morning, an address will be made by an outstanding exploration executive.

The general theme of the meeting will be exploration problems of certain future oil provinces of the South Central United States. It is proposed to present new and complementary papers covering the geology and geophysics, as well as the exploration problems, of the various provinces. In addition, there will be a few papers of general interest and a consideration of seismic velocity problems.

Similar meetings sponsored by these societies in past years have proven to be of great interest to those engaged in petroleum exploration throughout North America, and a large attendance at this meeting is expected.

In addition to the technical program, a dinner dance has been planned for the evening of Friday, December 1, at the Texas Hotel. The TCU-SMU football game will be played in Dallas on Saturday afternoon, December 2. Bus transportation from Fort Worth to the stadium and return will be arranged.

Hotel accommodations should be arranged for by individuals at the hotel or motor court of their choice.

James L. Morris, President of the Fort Worth Geophysical Society and H. C. Vanderpool, President of Fort Worth Geological Society, are General Co-Chairmen, and George H. Harrington, Jr., is Chairman of the Program Committee. T. R. Shugart is President of Dallas Geophysical Society, Richard Brewer, President of Ark-La-Tex, H. M. Thralls, President of Tulsa Geophysical Society and Lorenz Shock, President of Permian Basin Geophysical Society.

ANNOUNCEMENT OF JOINT ANNUAL MEETING

JEFFERSON HOTEL, SAINT LOUIS, APRIL 23–26, 1951

The joint annual meeting of the three petroleum exploratory societies, Society of Exploration Geophysicists, American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, will be held at the Jefferson Hotel, St. Louis, Missouri, on April 23, 24, 25 and 26, 1951. Notice of the meeting with hotel reservation request forms, will be mailed simultaneously to members of all three groups.

All requests for hotel rooms should be made by returning the application for Housing Accommodations form to the Hotels Reservation Bureau, A.A.P.G., 911 Locust Street, Room 406, St. Louis 1, Missouri. Requests for reservations should be made as far in advance of March 22, 1951 as possible, and should contain all information requested in the form. Receipt of requests will be acknowledged and filed in order of receipt at the Hotels Reservation Bureau. Actual assignments will be made in the various hotels and confirmations will be mailed about 60 days prior to the convention. Members who request reservations, but later find they can not attend should notify the Hotels Reservation Bureau without delay. Blocks of rooms will not be reserved. All rooms must be reserved in the names of individuals.

Officers, chairmen and committee members, particularly, are requested to reply promptly.

THE EXECUTIVE COMMITTEES

Tulsa, Oklahoma
October 15, 1950

PERSONAL ITEMS

DONALD N. MOONEY, student member of the society at The University of Tulsa, enlisted in the U. S. Air Force and now is located at Camp Lackly Field, San Antonio, Texas.

R. M. DREYER, chairman of the department of geology, University of Kansas, and Professor V. L. (Vic) Jones of The University of Tulsa are collaborating in experimental geophysical research. They have been conducting an extensive gravimetric and magnetic survey in Eastern Oklahoma during the past summer on this project, and they hope to have sufficient information to present a paper at the forthcoming annual meeting of the society.

A. E. (SANDY) MCKAY resigned as assistant chief geophysicist of The Atlantic Refining Company last June after having been with the company about 14 years. During the past six years he had resided in Dallas, Texas. He has been appointed executive vice president of Southern Geophysical Company with headquarters at 600 Bailey, Fort Worth, Texas. Sandy has been in geophysics for about 18 years since receiving the degree of B.S. in geology in 1928 from the University of Oklahoma. He was the first president of the Dallas Geophysical Society.

M. MICHAEL ALLON has become president of the Alberta Exploration Company Limited, with head offices at 607 Lancaster Building, Calgary, Alberta. Mr. Allon formerly served as geophysicist on a seismograph party for Gulf Research and Development Company, located in Pincher Creek, Alberta. His address remains Box 355, Pittsburgh 30, Pa.

V. G. FEATHER has resigned from the Honolulu Oil Corporation as geologist-seismologist, and has opened offices as geophysical consultant at 407 N. Garfield, Midland, Texas.

T. A. MANHART, Clark Millison and B. W. Beebe announce the formation of an exploration consulting partnership called Manhart, Millison and Beebe, with temporary offices at 624 East Fourth Street, Tulsa, Oklahoma. They will perform all types of geological and geophysical services in domestic and foreign areas, with emphasis on programs which require coordination and direction from inception to completion. Among the activities of the firm are services as geophysical and geological advisers to Petroleos Mexicanos, and the direction and coordination of several exploratory programs in the United States and Canada.

SIDON HARRIS, president of Southern Geophysical Company, announces removal of their offices and laboratory to their new building at 600 Bailey Avenue in Fort Worth, Texas.

A. J. HINTZE, formerly chief geophysicist, has become manager, exploration section of Phillips Petroleum Company, Bartlesville, Oklahoma. W. H. Courtier, formerly assistant chief geophysicist, has become chief seismologist.

ALBERT JOHNSON has joined Sharpe Instrument Company, Limited, as general manager. The company, engaged in manufacturing and distributing geophysical and surveying equipment, is located at 690 Bay Street, Toronto, Canada.

GEORGE A. GRIMM has resigned as party chief for Seismograph Service Corporation, and has joined Tidewater Associated Oil Company as district geophysicist with headquarters in Midland, Texas.

H. WAYNE HOYLMAN, formerly chief geophysicist of Fairchild Aerial Surveys, Inc., Los Angeles, has established his office as consulting geophysicist at 815 Architects Building, 816 West Fifth Street, Los Angeles 17, California. While engaged in various phases of geophysical work, he is specializing in the interpretation of airborne magnetics. Prior to joining Fairchild in 1948, he had been associated with Gulf Research and Development Company since 1930, and was active in the development of the company's airborne magnetometer operations.

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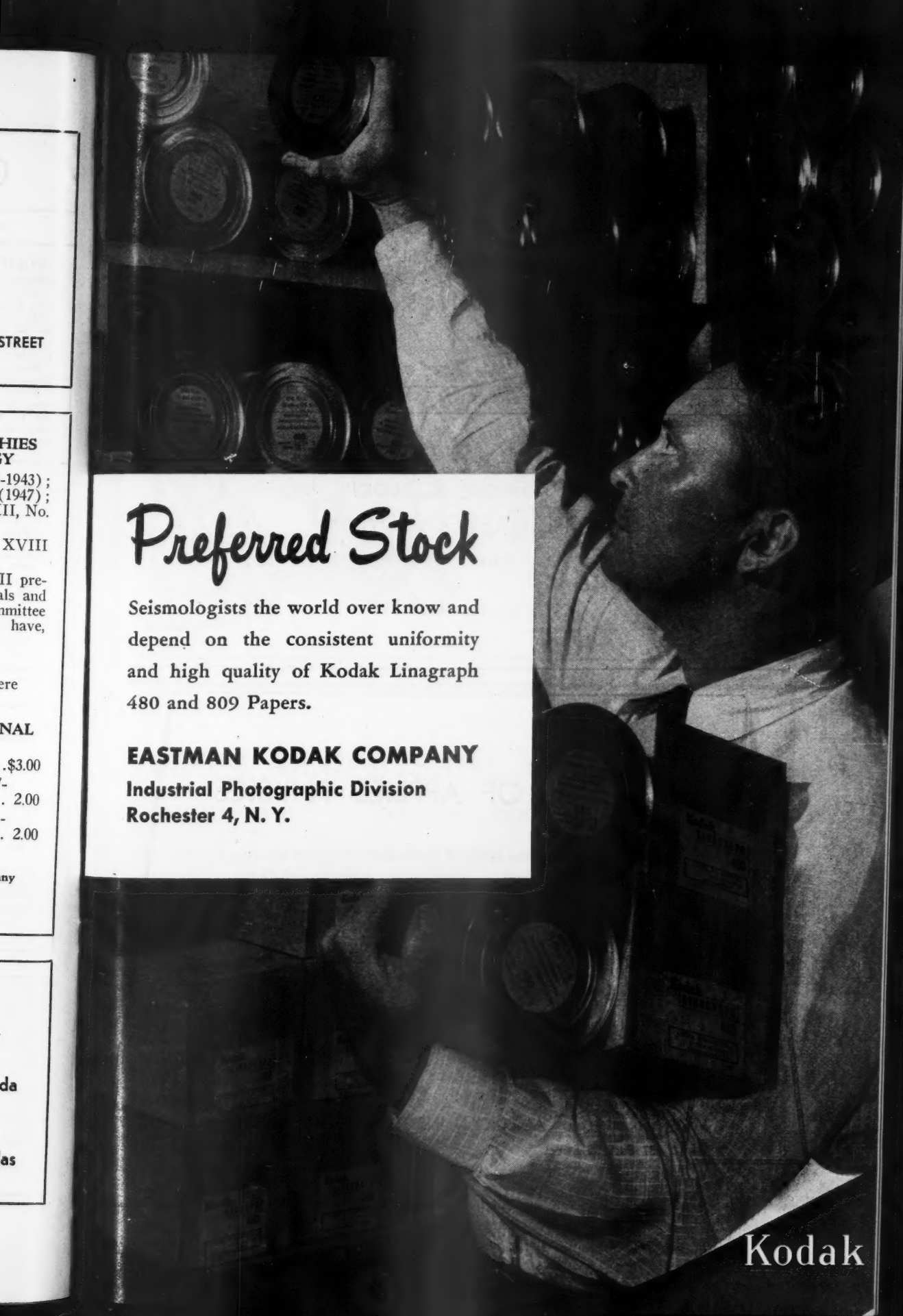
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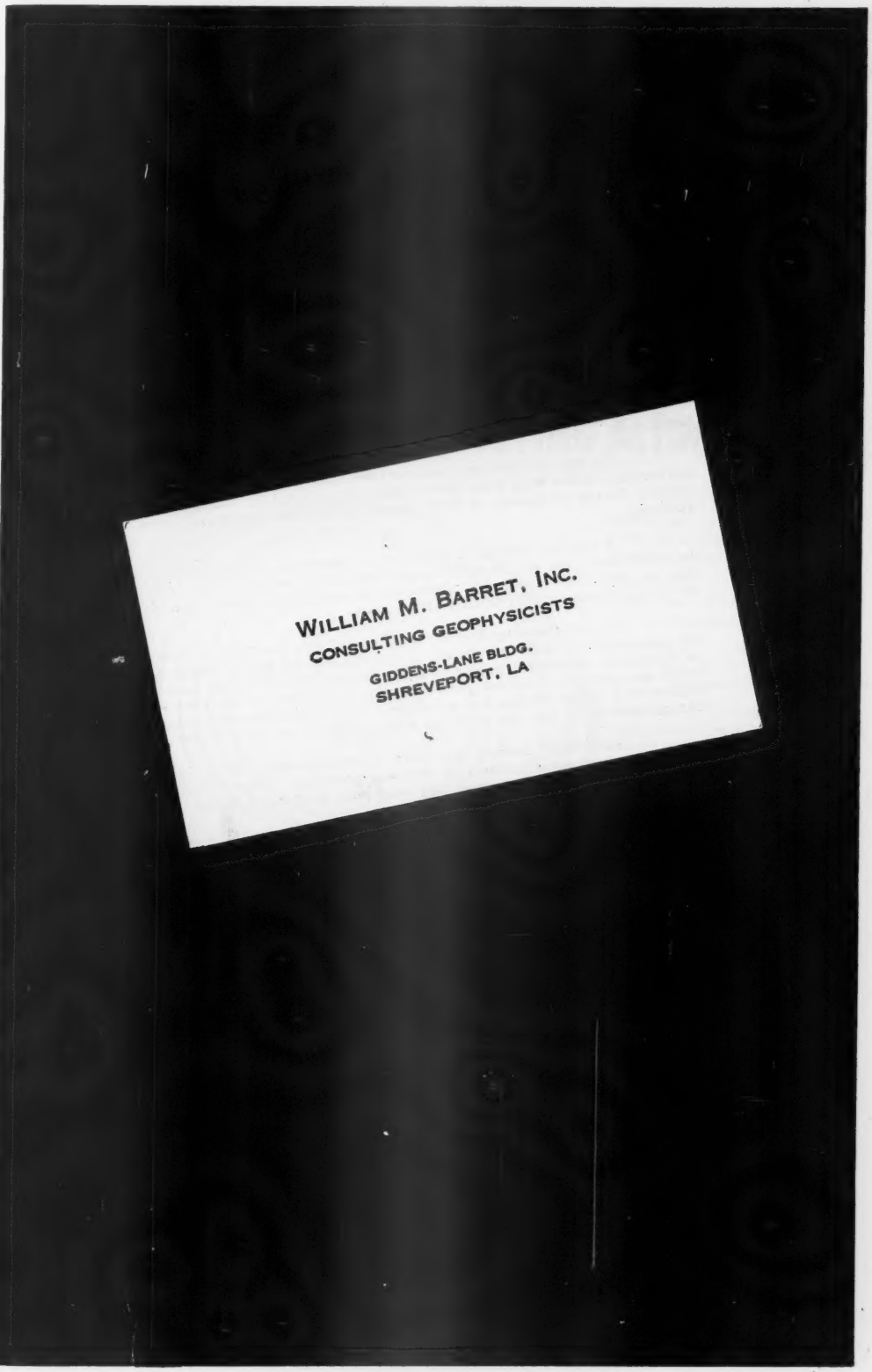
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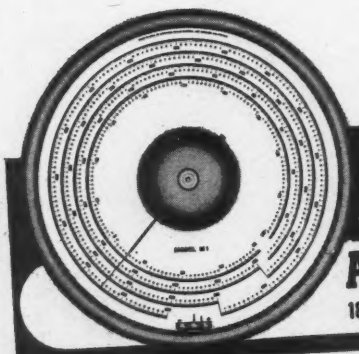

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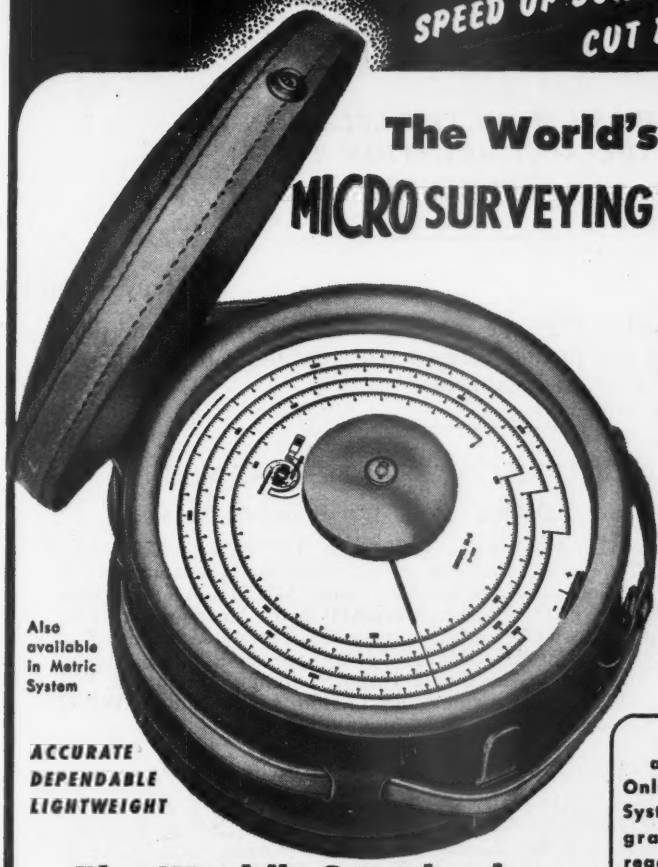

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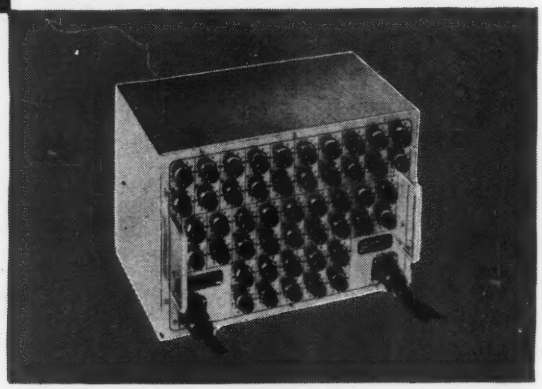

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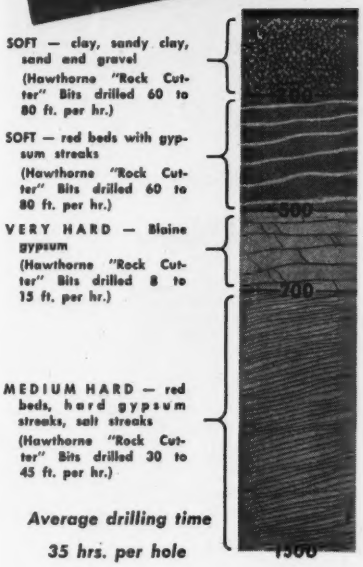
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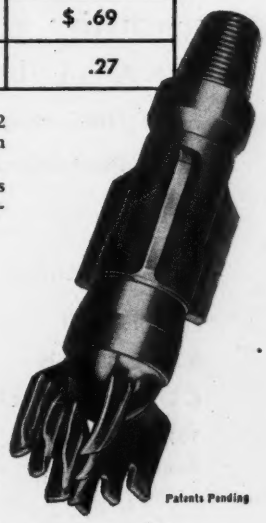

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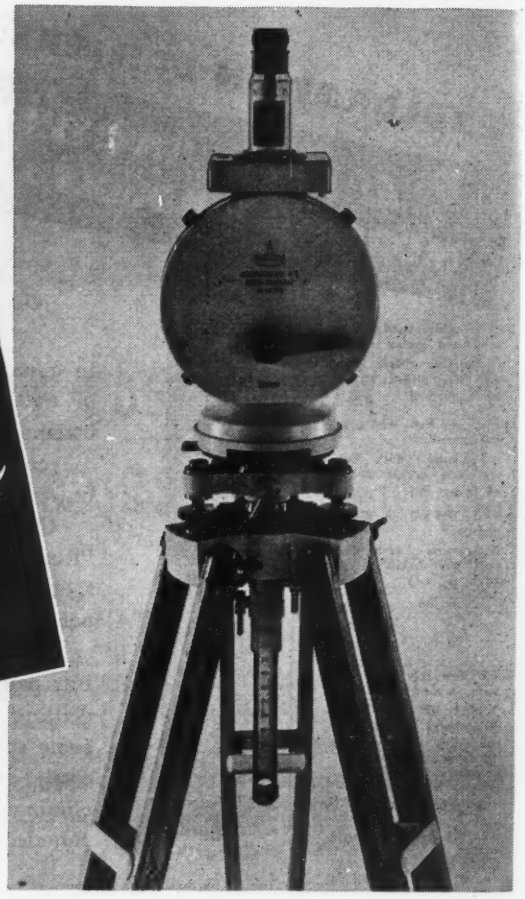

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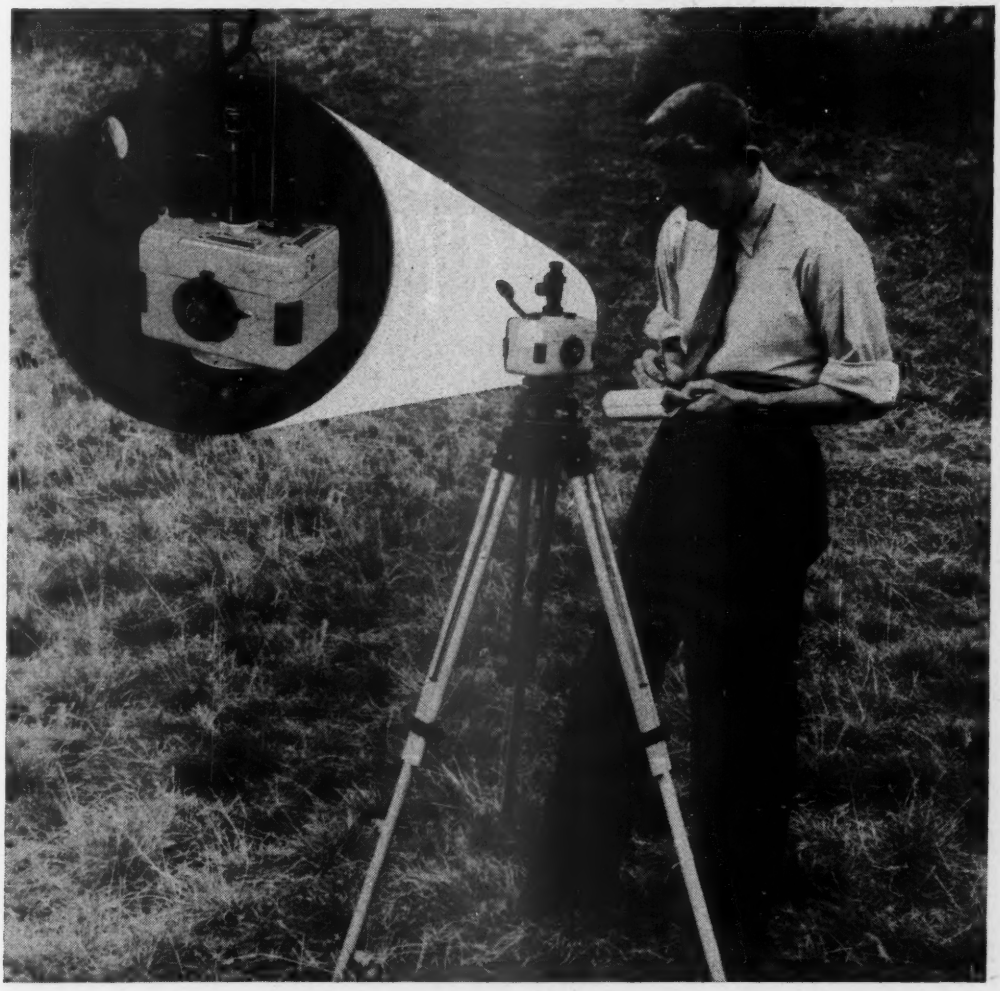

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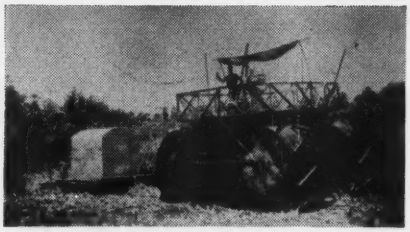

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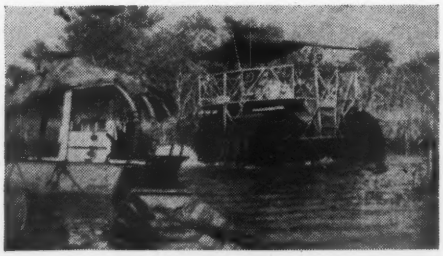

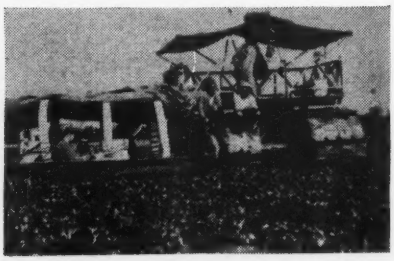

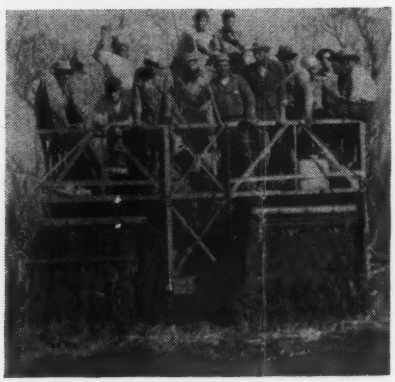

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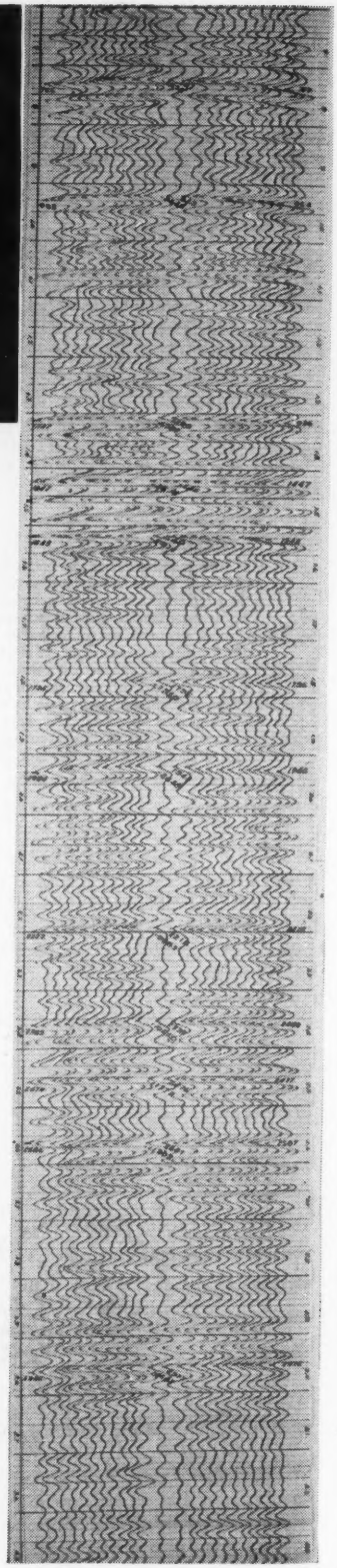

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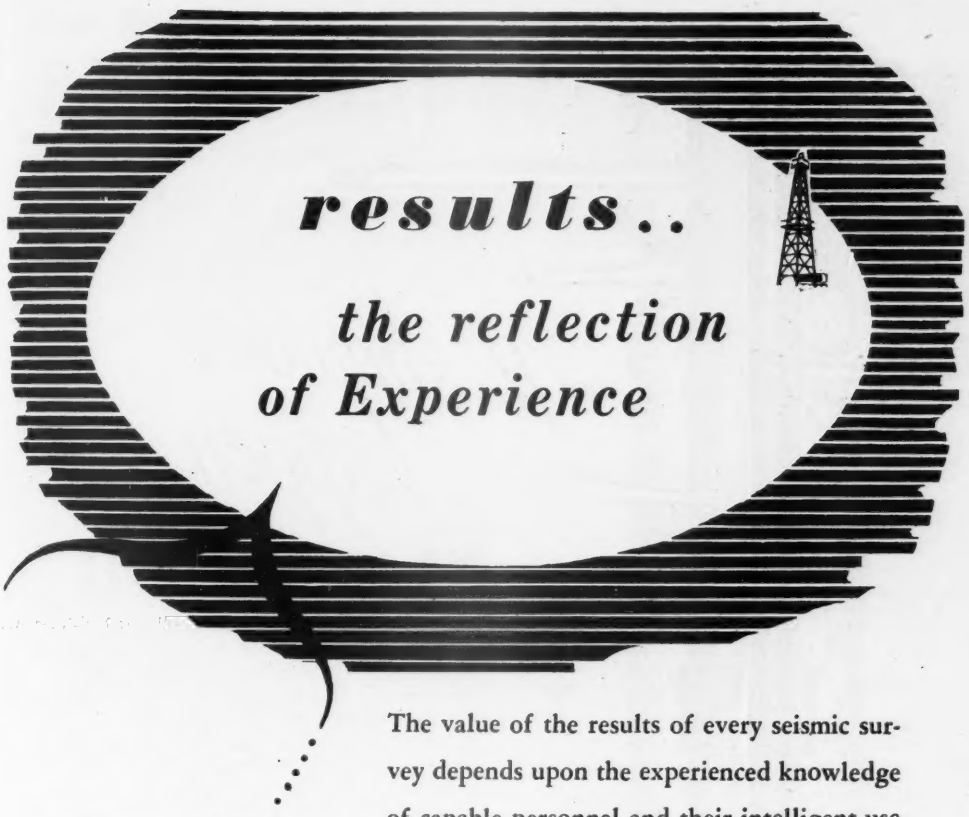

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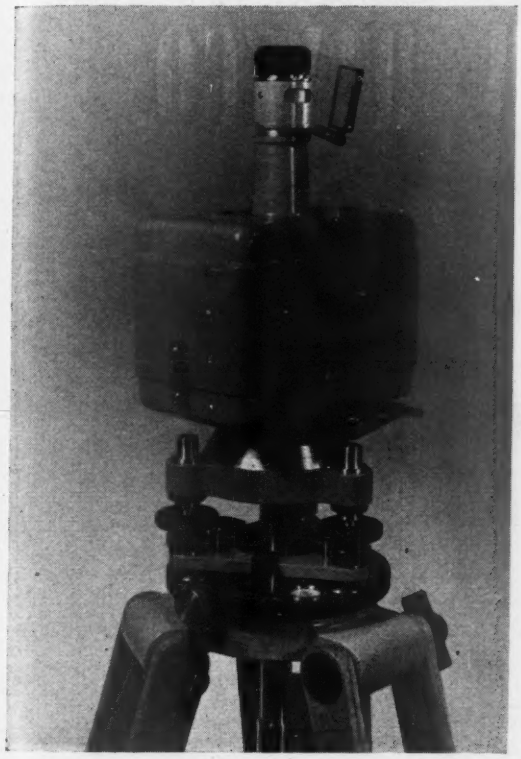

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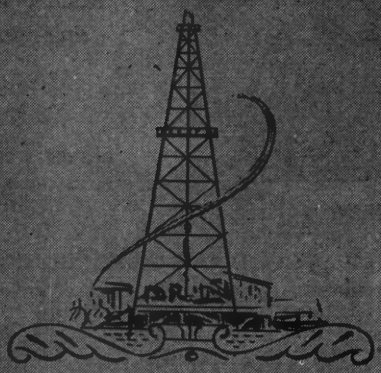

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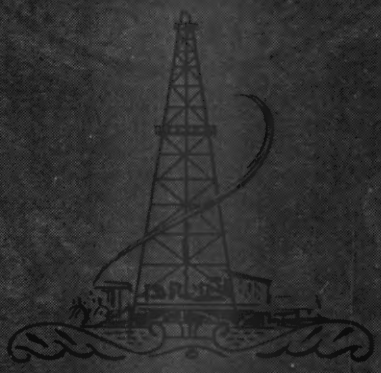

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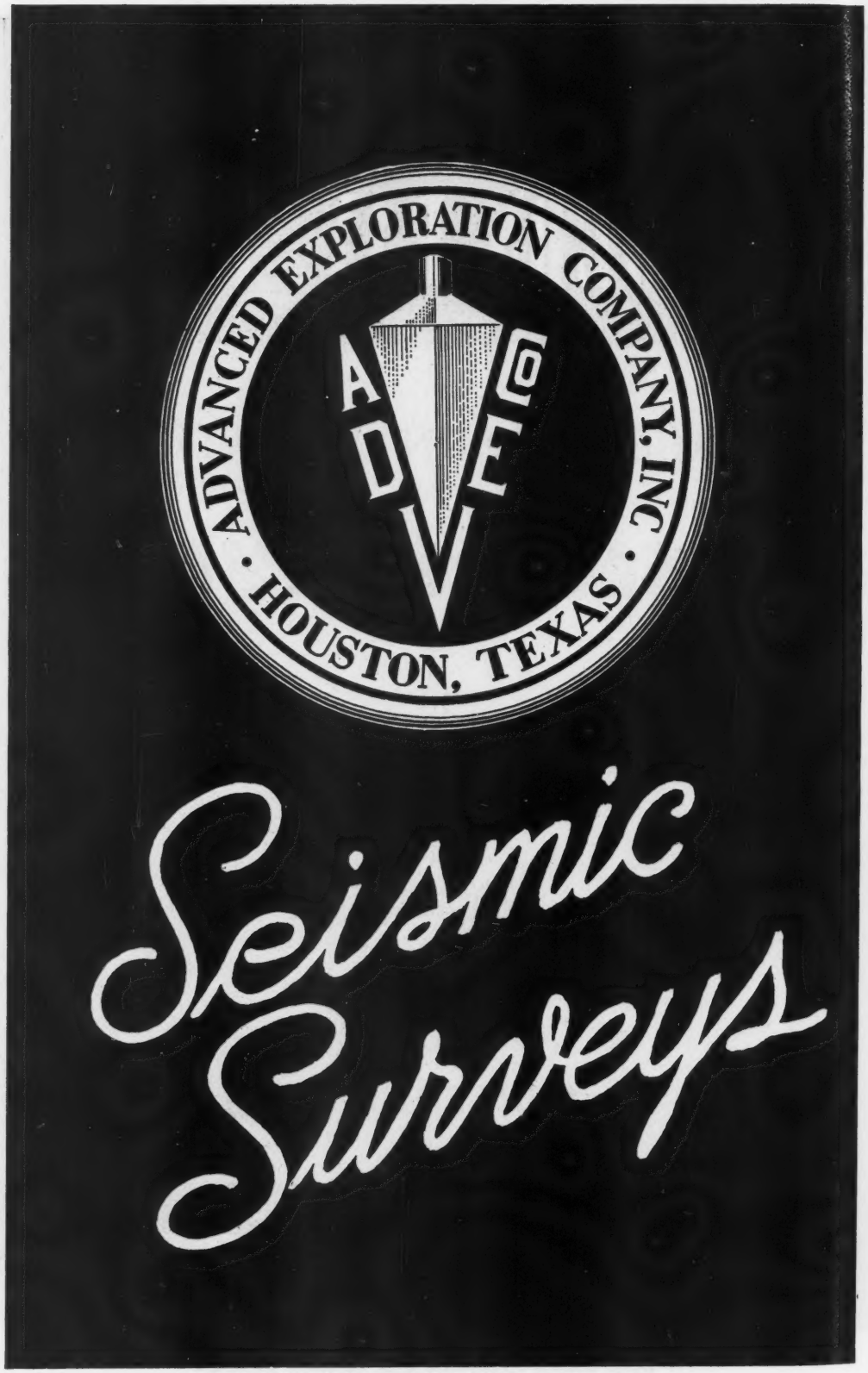
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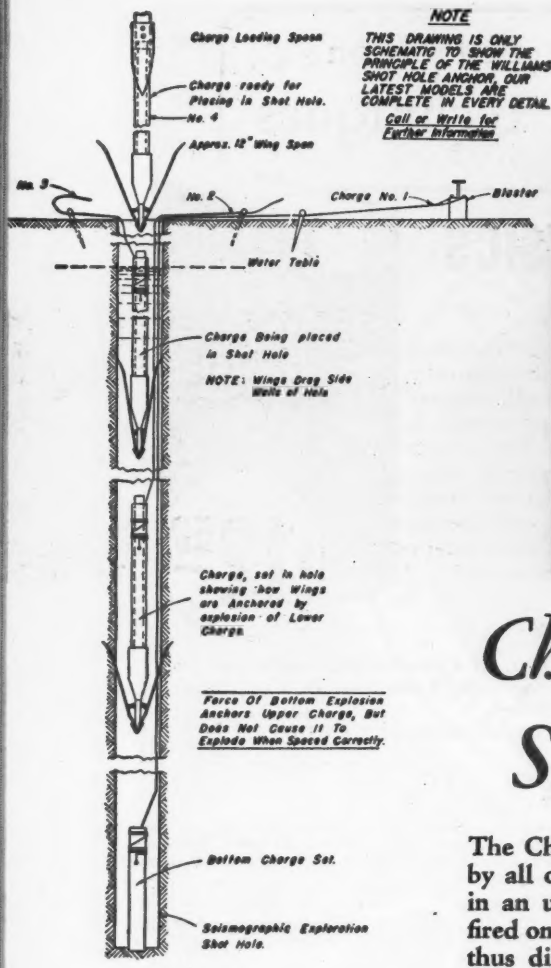
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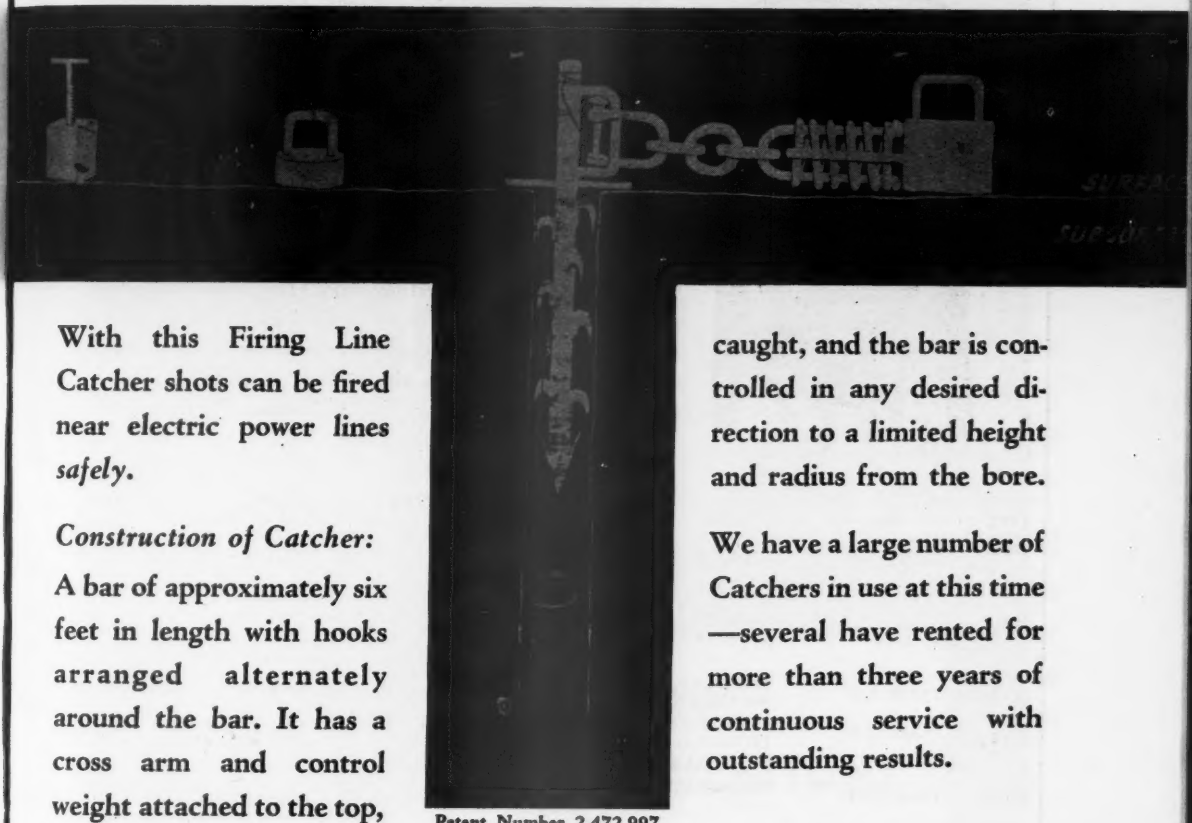

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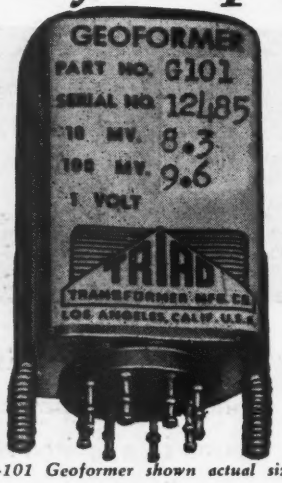

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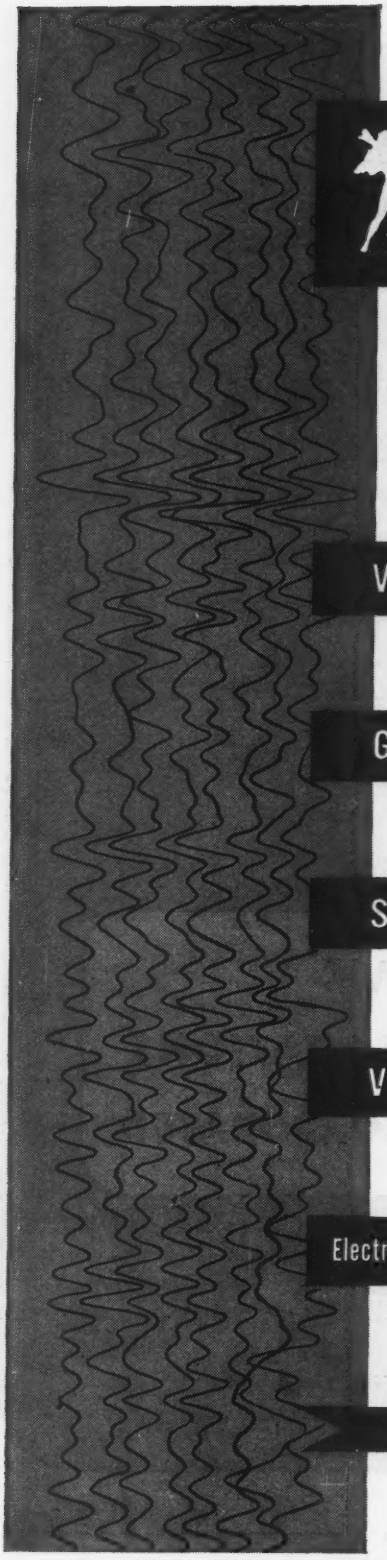

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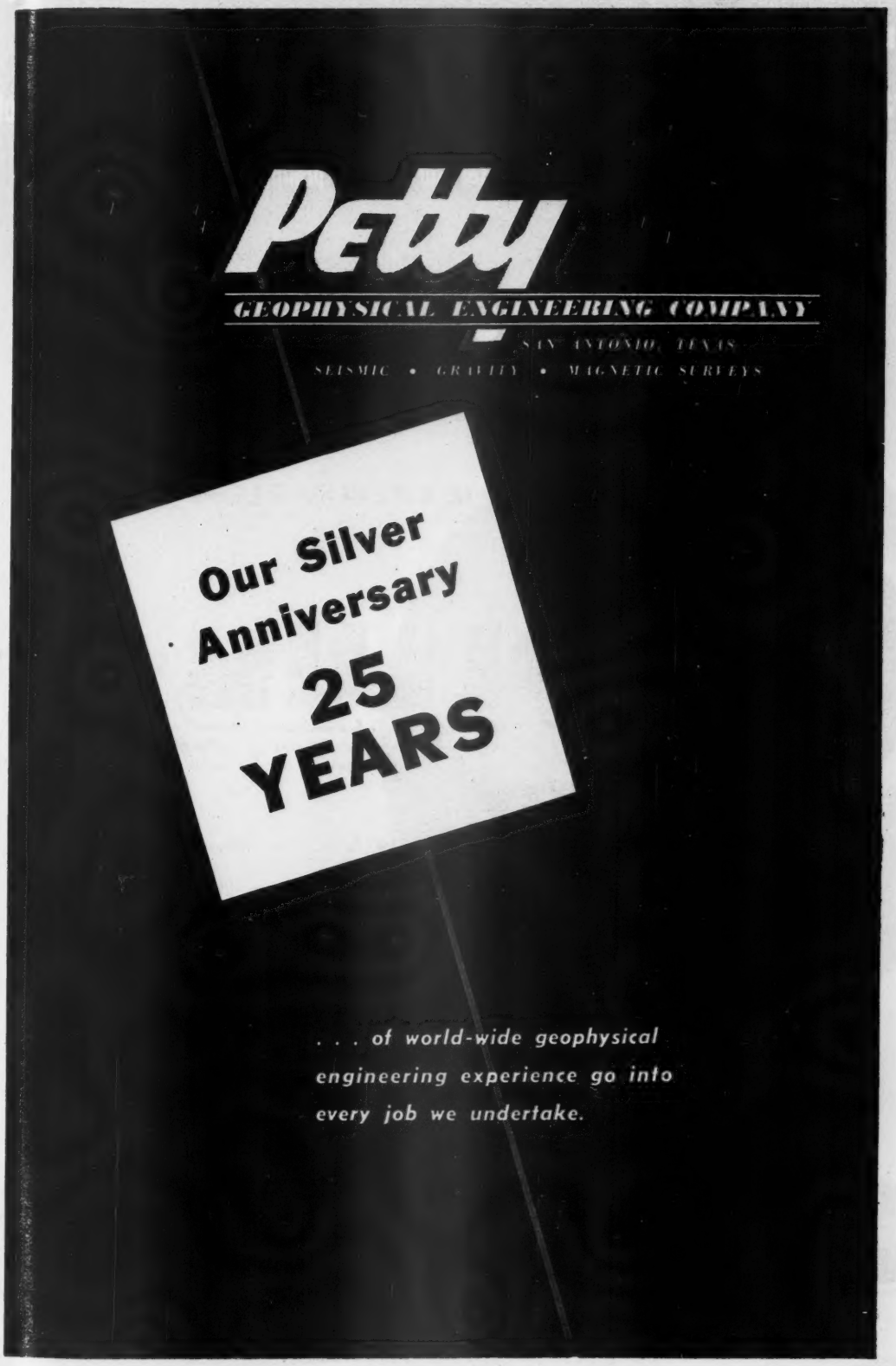
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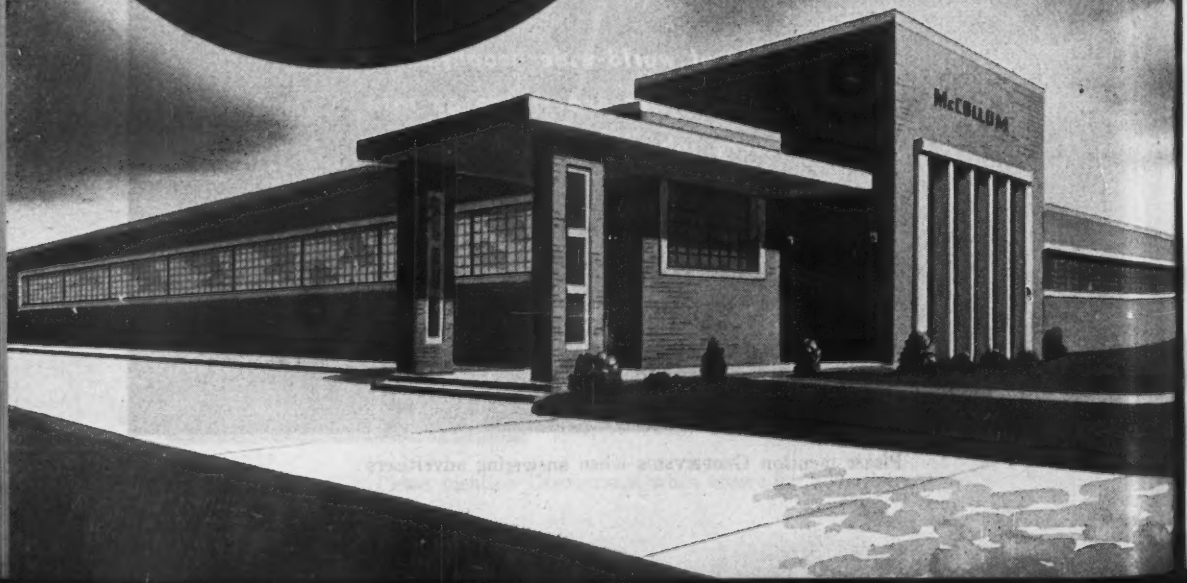

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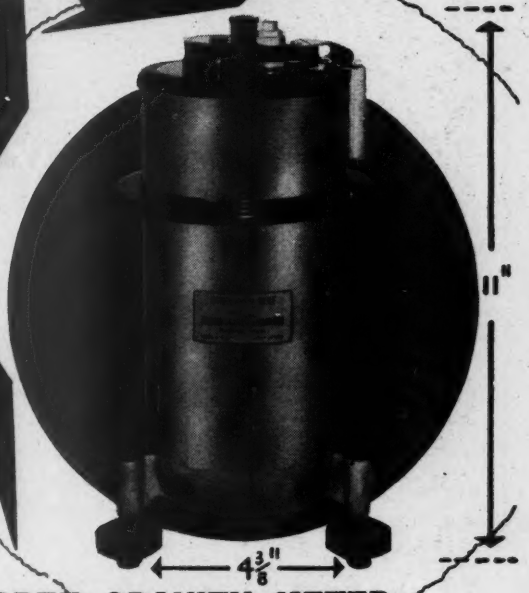

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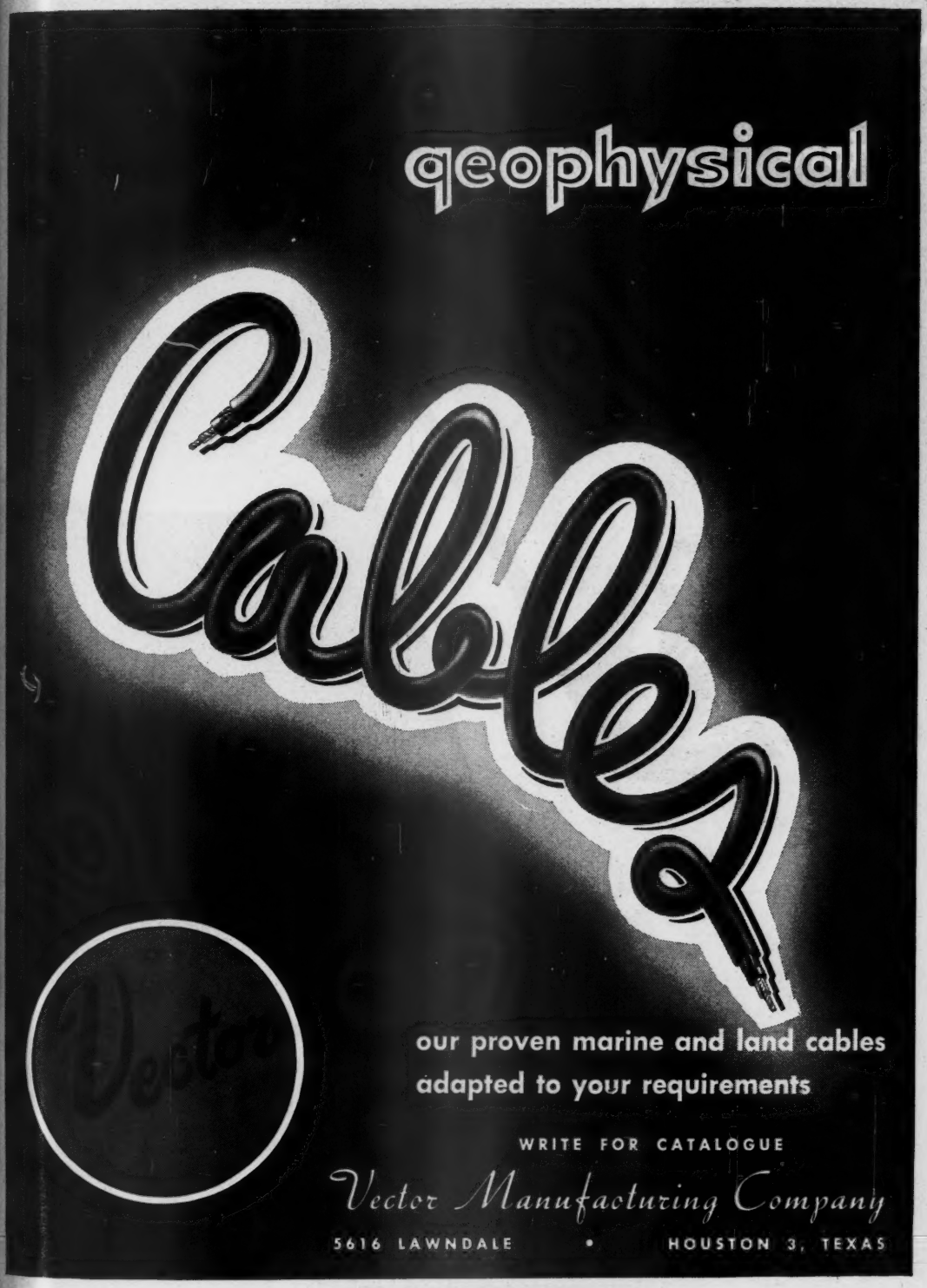
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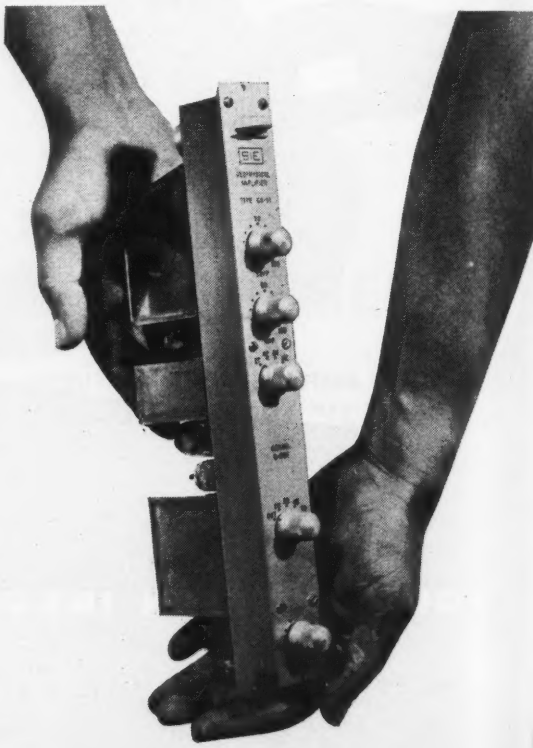
FILTERING: A straightforward LC Band Pass filter is used. There are two sections for low frequency rejection and one section for high frequency rejection. This provides not only a choice of filter peaks, but also a choice of a narrow or wide pass band, as desired. If a gentle slope on the low frequency side is desired, one section of low frequency filter may be switched out of the circuit. If full low frequency response is desired, both sections of low frequency filter may be switched out of the circuit. The many filter combinations provide complete flexibility of operation which allows the geophysicist to obtain maximum recorded results from any area. The GA-11 filter system is equal, or superior, to most full sized equipment in the field today.

AUTOMATIC GAIN CONTROL: The GA-11 Amplifier provides a truly superior AGC system. The very fast operate time at the first events insures excellent "front end" control and allows perfect recording of extremely shallow events. The much slower operate time "out in the record" allows for a great deal of amplitude character in the reflected events: thus, reflections are shown in their true relationship. This excellent AGC action is made possible by the use of two passive control elements, whereas most seismic amplifiers embody only one control element. A single mesh filter network in the AGC circuit insures against over-control or "pinch-off" from large bursts of energy. Thus, even those events which follow other events closely, are recorded faithfully. The unusually wide range of the AGC prevents distortion from high input levels. The AGC is fully capable of handling the entire record without the aid of initial suppression.

INITIAL SUPPRESSION: Each amplifier is provided with an individual initial suppression control, by means of which the suppression can be turned on or off or individually adjusted. Thus, the correct amount of suppression for each trace may be applied, as in the case of very strong first events near the shot hole and very weak first events near the end of the spread. A master suppression control on the control panel provides for varying the suppression of all amplifiers simultaneously. Initial suppression in the GA-11 Amplifier is accomplished by pre-loading of the AGC circuit. This is one of the primary reasons for the excellent "front end" control at the first events.

AMPLITUDE CONTROL: Each GA-11 Amplifier is provided with an individual record level control which consists of an attenuator between the amplifier and the galvanometer. Thus, the average amplitude of the individual traces may be set to any desired level.

POWER REQUIREMENTS: The 12 channel unit, including the camera, requires 11.5 amperes from the 12 volt battery. The 24 channel unit requires a total of 21 amperes from the 12 volt battery. During the actual time the camera is recording (3 or 4 seconds per record), the



current required is increased by 7 amperes. The 12 volt 34 ampere hour aircraft battery normally furnished has operated a 12 channel P-11 Unit for two full days of normal recording.

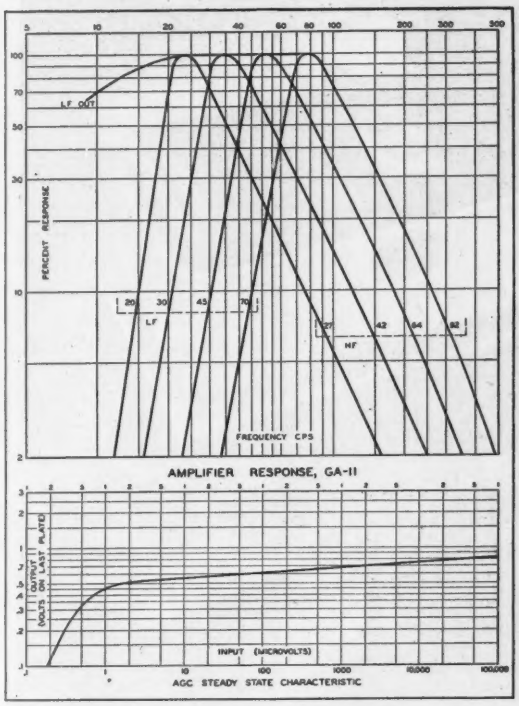
TUBES: The GA-11 Amplifier is not critical with regard to "tube matching." Each channel contains one standard 12AY7, two standard 12AU7, and two standard 6AL5 tubes, all of which are readily accessible for replacement.

PLUG-IN CONSTRUCTION: The GA-11 is a plug-in type amplifier and may be replaced in a few seconds by removal of two screws on the panel. No soldering is necessary.

HERMETIC SEALING: All components, including capacitors, resistors, transformers and chokes, are vacuum dried and enclosed in hermetically sealed cans.

DIMENSIONS: The GA-11 Amplifier measures 1⅜" x 3¾" x 12¼".

WEIGHT: The GA-11 Amplifier weighs 2 pounds, 10 ounces.



AMPLIFIER RESPONSE, GA-11

AGC STEADY STATE CHARACTERISTIC

THE PSU-11 AMPLIFIER UNIT

(See Front Cover . . .)

GENERAL: The 12 trace PSU-11 Amplifier Unit contains 12 GA-11 Amplifiers, plus all necessary manual and automatic control circuits. The entire unit is contained in a waterproof aluminum carrying case which measures 6" x 13" x 21" and weighs 40 pounds. On special order, the PSU-11 Amplifier Units can be furnished with any number of channels.

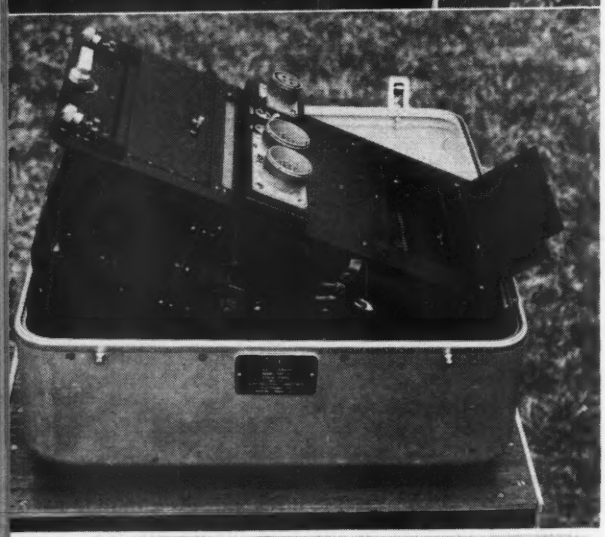
CONTROL EQUIPMENT: The PSU-11 Amplifier Unit has control panels located at either end of the amplifier case, from which all control functions, both manual and automatic, are handled. The automatic functions include removal of the initial suppression, initiation of mix circuit, and removal of time break and up-hole energy from the galvanometers. The manual functions include power "ON" and "OFF," mixing circuit "ON" and "OFF," and the sensitivity and trace selection of the automatic trip amplifier.

MIXING: The mixing circuit consists of bi-directional resistive output mixing. The percentage of this mixing is usually set at 20%, but may be varied to suit individual taste. (Should be specified when ordering.) The mixing circuit is held out until all of the first breaks are received.

NOTE: It is realized that mixing is still a controversial subject. Therefore, should a geophysicist desire a different type of mixing, it can be included in the PSU-11 Amplifier Unit at slight additional cost.

COMMUNICATION: Sound powered telephones are used for communication. Plugs are provided for both the telephone line and handset. Normally, the time break and up-hole geophone are brought in on the telephone line. However, for those who prefer the up-hole geophone to appear on a separate trace with amplification, this feature can be furnished at slight additional cost.

24 CHANNEL: Two PSU-11 Units are used for recording 24 traces.



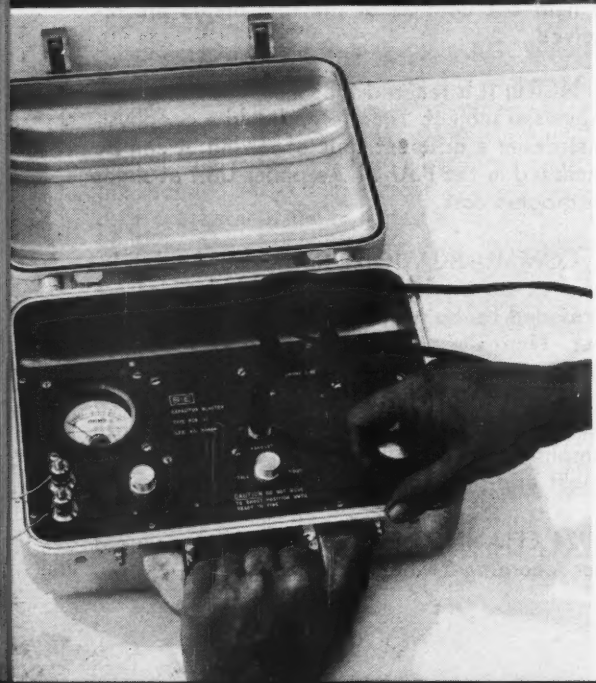
THE PRO-11 OSCILLOGRAPH

DIMENSIONS AND WEIGHT: The PRO-11 measures 8 inches by 9 inches by 16 inches and weighs approximately 25 pounds.

GALVANOMETERS: The PRO-11 may be furnished with as many as 25 galvanometers. These are individually sealed barrel type galvanometers, and are electro-magnetically damped. The curves shown at the right are from a standard galvanometer. However, other frequencies are available on special order. The galvanometers are all readily accessible for adjustment or replacement through the small door on the front panel.

VIEWING SCREEN: The traces appear on the viewing screen in the same relation as they appear on the record itself.

TIMING SYSTEM: The timing system is completely contained in the oscillograph. A pre-



THE PCB-11 BLASTER

The PCB-11 incorporates the detonator, cap testing circuit, and shooter's communication in one compact unit.

The detonator is a capacitor type which provides a terrific firing current. There is no appreciable time lag in firing the cap. The time break is well defined and consistent on every shot.

The cap testing circuit makes use of one silver chloride cell which cannot possibly detonate the cap. An open or shorted firing line is instantly indicated on the meter.

The shooter's sound-powered telephone plugs directly into the blaster for communication with the recording truck.

The PCB-11 measures 5 inches by 9 inches by 12 inches and weighs approximately eight pounds.

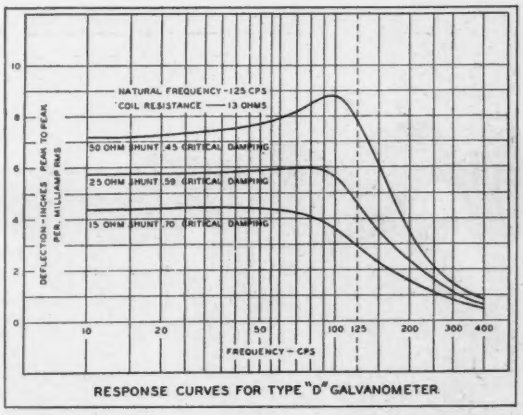
cision, bimetallic temperature compensated tuning fork, driven by carbon buttons, provides time intervals accurate to one part in 100,000. The fork operates a specially designed synchronous timing motor, which operates the light valve. Lines of different intensity are placed on the record at 1/10, 1/20 and 1/100 second intervals.

LIGHT INTENSITY: When taking a record the light intensity is automatically increased. This feature helps conserve batteries and prolongs the life of the light bulbs.

MAINTENANCE: All components are readily accessible for replacement in the field.

STORAGE MAGAZINE: The PRO-11 accommodates 150 feet of six-inch paper. Narrower paper widths may be used with proper spacers.

RECORD MAGAZINE: The record magazine is readily removable and is completely light-tight.



RESPONSE CURVES FOR TYPE "D" GALVANOMETER

PAPER KNIFE: The paper knife is built into the record magazine and acts as a light seal when operated.

PAPER DRIVE: A 12-volt, governor-controlled motor with integral reduction gear furnishes power for the positive drive feed rollers. The governor normally provides a speed range of 10 to 15 inches per second; however, other speed ranges are available on special order.

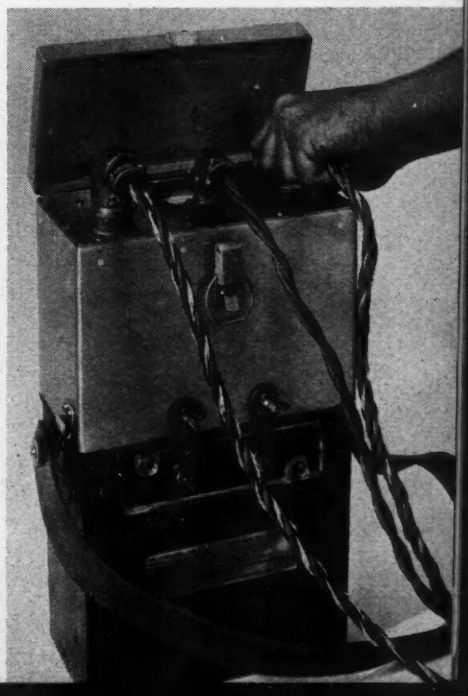
THE PPS-11 POWER SUPPLY

The primary source of power for the P-11 Seismograph is a 12 volt aircraft type lead acid storage battery, rated at 34 ampere hours.

Mounted on top of this battery is the PPS-11 Power Supply Unit, which consists of a small efficient dynamotor, filter, necessary contact relays, and interconnecting plugs.

The entire unit, including the battery, measures 6 inches by 12 inches by 18 inches, and weighs approximately 50 pounds.

A complete 12 trace P-11 Unit has been operated for two full days of normal shooting from this power supply without re-charging the battery.



SOUTHWESTERN INDUSTRIAL ELECTRONICS CO.

PERFORMANCE *PLUS* PORTABILITY

After years of intensive research S. I. E. has developed a seismograph to fulfill the requirements of the most exacting geophysicist. The P-11 provides all of the features and performance characteristics of full-sized truck-mounted instruments plus the additional advantage of true portability.

The geophysicist is no longer restricted to roads and high ground when shooting swamps, jungles, deep snow or other difficult areas. Each unit of the P-11 Seismograph is the correct size and weight to fit comfortably on a back pack and can be carried anywhere that a man can go.

Despite Adversities of Climate and Terrain the P-11 Gets the Records

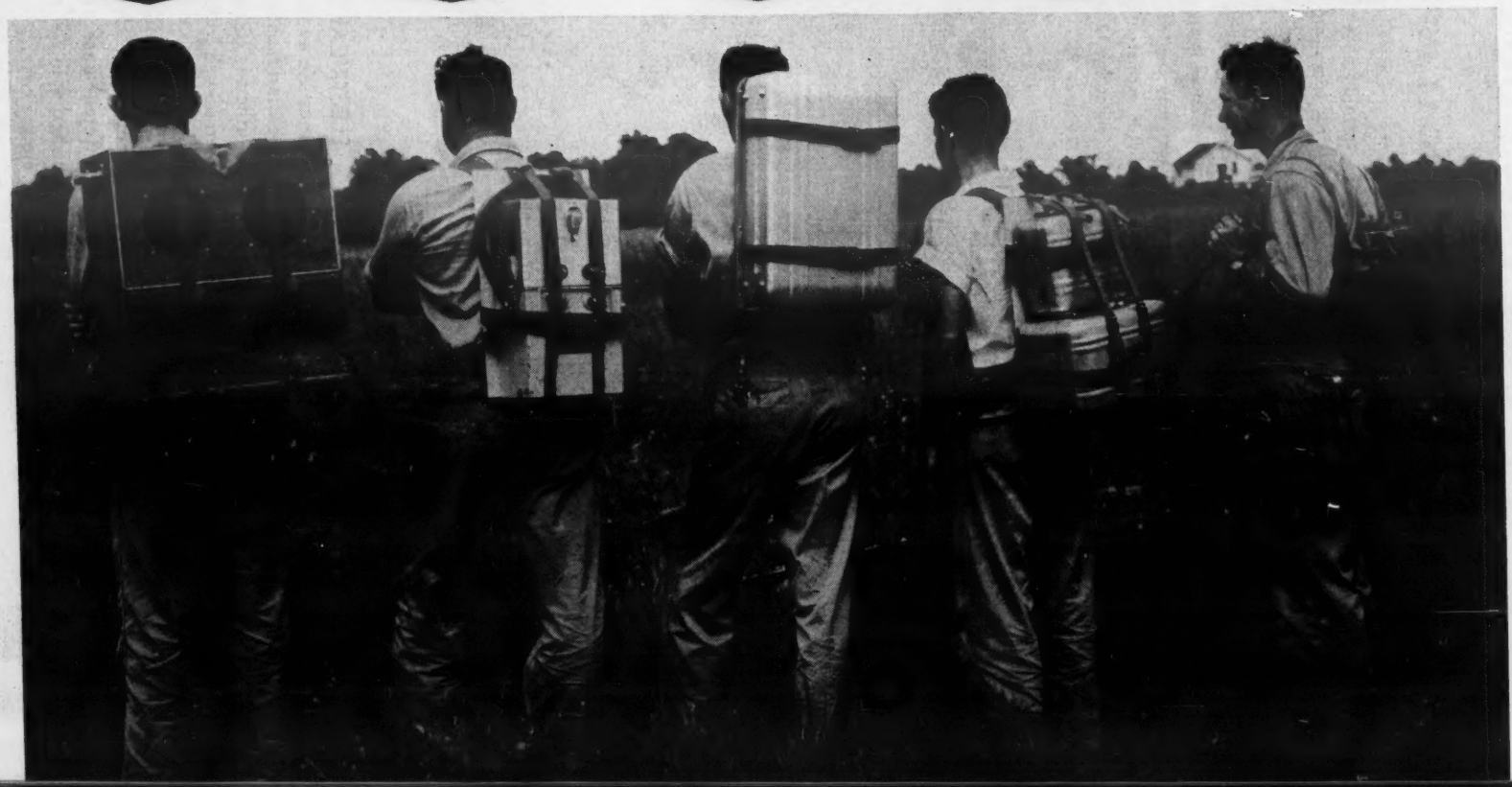
PDU-11 DEVELOPING UNIT CONTAINS THREE SPLASH PROOF, STAINLESS STEEL DEVELOPING POTS. MEASURES 12 IN. X 17 IN. X 20 IN. AND WEIGHS 50 LB. FULL.

PPS-11 POWER SUPPLY AND 12-VOLT, 34 AMP. HR. BATTERY MEASURES 6 IN. X 12 IN. X 18 IN. AND WEIGHS 50 LBS.

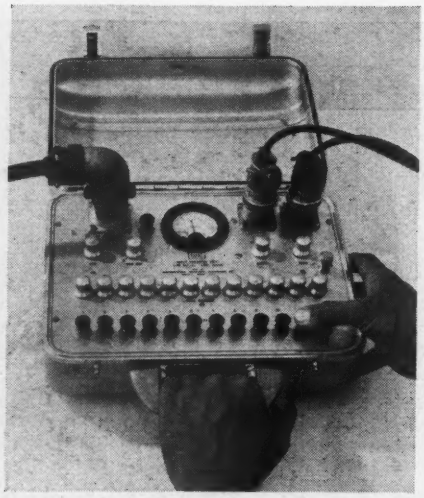
PSU-11 AMPLIFIER UNIT CONTAINS 12 TYPE GA-11 AMPLIFIERS AND CONTROL CIRCUITS. MEASURES 6 IN. X 13 IN. X 21 IN. AND WEIGHS 40 LBS.

ABOVE: PCB-11 BLASTER MEASURES 5 IN. X 9 IN. X 12 IN. AND WEIGHS 8 LBS. BELOW: PRO-11 OSCILLOGRAPH MEASURES 9 IN. X 9 IN. X 16 IN. AND WEIGHS 25 LBS.

25 TYPE S-15 GEOPHONES AND TWO 1000 FT. MULTICONDUCTOR GEOPHONE CABLES WITH REELS TOTAL WEIGHT 50 LBS.



SOUTHWESTERN INDUSTRIAL ELECTRONICS CO.



THE PIC-11 INPUT CHECKING UNIT

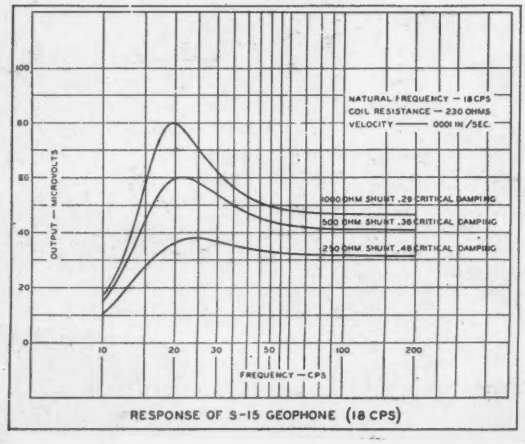
A convenient and useful auxiliary unit, the PIC-11 is not necessary for the operation of the P-11 Seismograph. The geophone test circuits provide a convenient check for continuity of all geophone lines before taking a record. Individual potentiometers are provided for each trace to balance out excessive power line interference. These line balancers may be turned off at will. For testing and matching purposes, an input paralleling switch is provided in order that all traces may be fed from a common geophone or from the local built-in oscillator. The 12 trace PIC-11 Unit measures 5 inches by 9 inches by 12 inches and weighs approximately 10 pounds. The 24 trace PIC-11 Unit is slightly larger.

THE S-15 GEOPHONE

WEIGHT AND DIMENSIONS: The S-15 flat-base Geophone weighs 11 ounces and measures 1⅝" in diameter by 1⅝" in height. With 1¾" spike, the S-15 weighs 13 ounces.

DURABILITY: Many thousands of these rugged little detectors are in actual field use, and daily they furnish proof of their excellent fieldworthiness.

SENSITIVITY: The sensitivity of the S-15 compares favorably with standard size detectors. When used with the P-11 Seismograph, a single detector per trace is standard practice.



RESPONSE OF S-15 GEOPHONE (18 CPS)

ELECTRICAL CHARACTERISTICS: S-15 Geophones are available in a wide range of impedances and frequencies. The standard impedance furnished is 200 ohms. Frequencies are available from 15 cps to 40 cps.

CASE TYPES: To meet individual requirements, these detectors are available in several different case arrangements. They may be furnished with flat base, with spike, or with special marine case.

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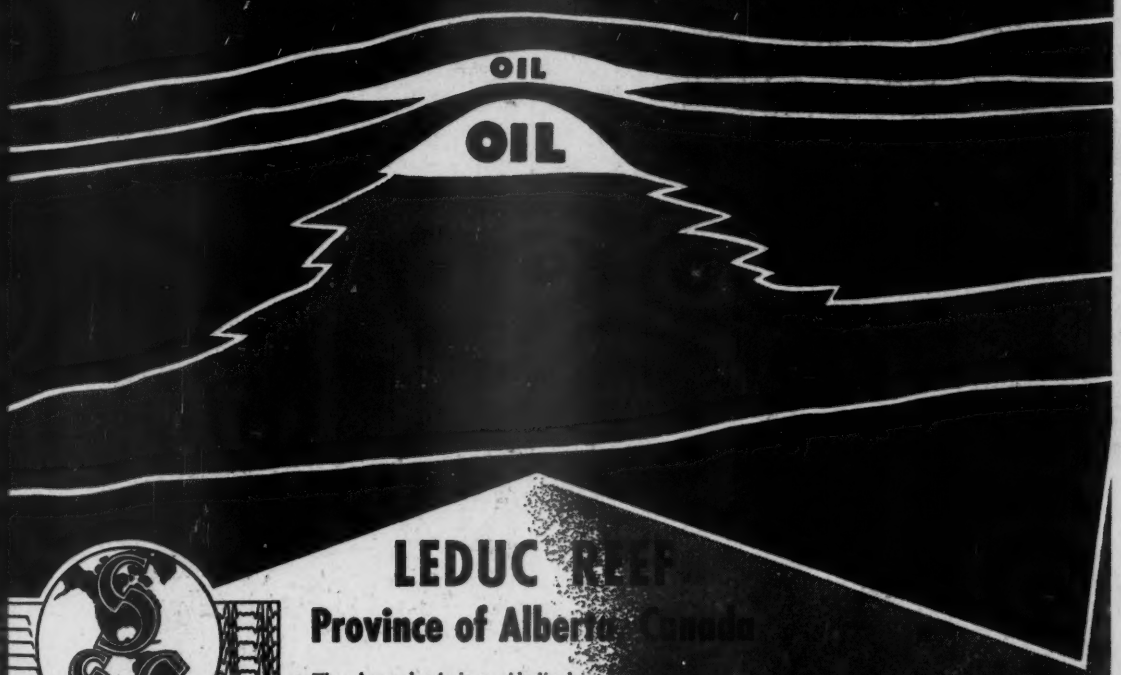
Are you looking for Reefs?



LEDUC REEF
Province of Alberta, Canada

The above sketch is an idealized conception of the general geologic features.

The Leduc (D3) reef is a medium-sized, dolomitized reef of Upper Devonian age. It is considered to be a transgressive-type reef, and during its life probably resembled a modern Pacific atoll. A shale blanket overlies the reef, and acts as a seal for the oil in the reef reservoir. Immediately above this shale there is another dolomitized Devonian oil-producing zone — the D2 — which is probably biostromal in origin.

The overlying formations are draped over the reef, the amount of draping diminishing rapidly away from the reef. Oil and gas shows have been found above the reef in sandy facies in the Cretaceous formations. The Leduc reef has a maximum thickness of about 700 feet. The highest and most productive part is along the northeast edge, where the oil and gas zone is 230± feet thick.

SSC Recommends the Following Approach for Seismic Reef Exploration.

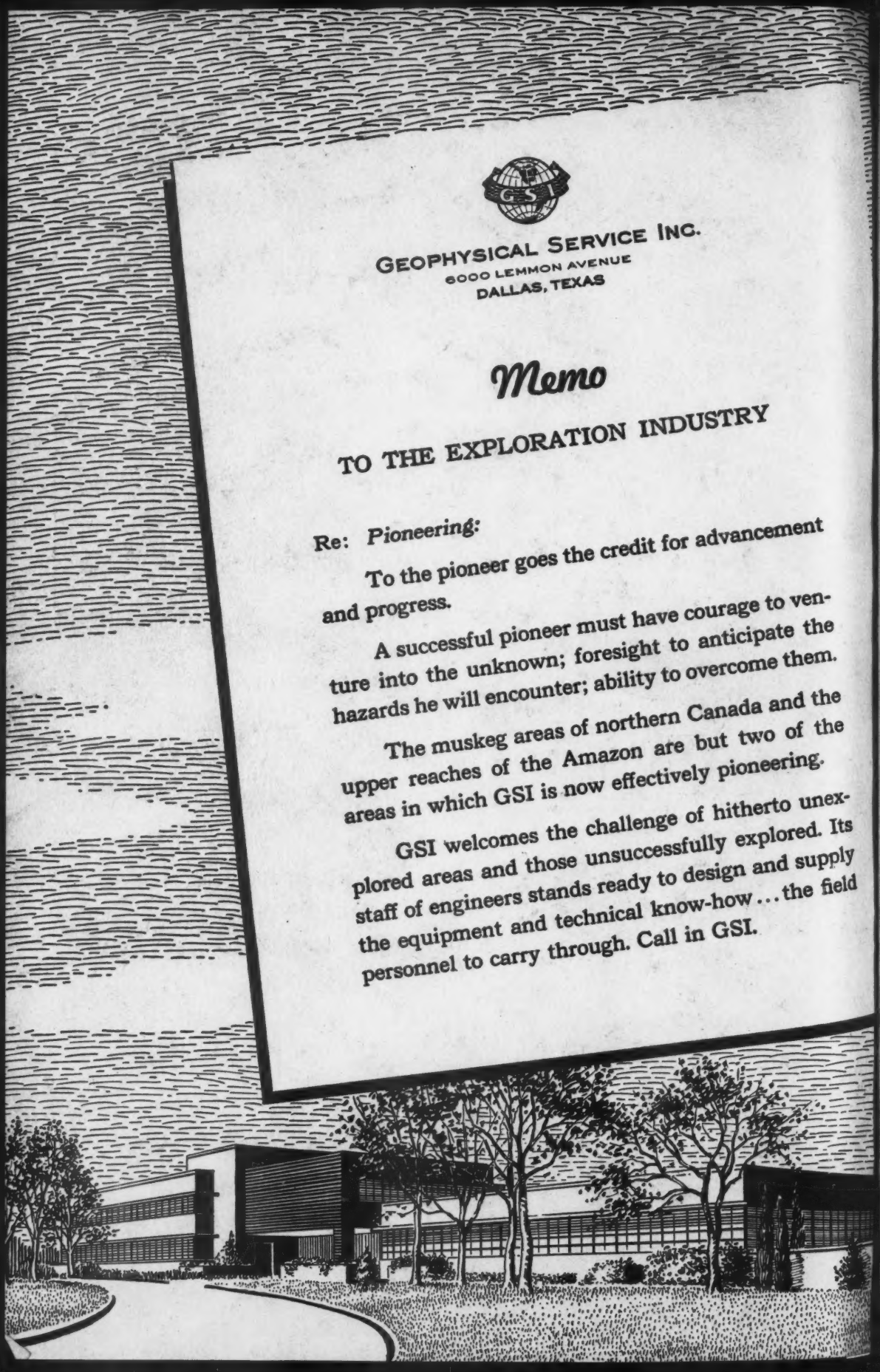
NO. 2 DETAILED SURFACE AND SUBSURFACE COVERAGE

The delineation of the anomalous subsurface conditions usually associated with organic reefs requires a close spacing of subsurface depth points. This implies not only a close spacing of geophones, but also a close spacing of closed traverses on the surface. CONTINUOUS PROFILING, originally developed by SSC, is the ONLY procedure that furnishes coverage sufficiently detailed for a successful reef exploration program.

(This is one of a series)

Seismograph Service Corporation

TULSA, OKLAHOMA, U. S. A.



GEOPHYSICAL SERVICE INC.
6000 LEMMON AVENUE
DALLAS, TEXAS

Memo

TO THE EXPLORATION INDUSTRY

Re: *Pioneering:*

To the pioneer goes the credit for advancement and progress.

A successful pioneer must have courage to venture into the unknown; foresight to anticipate the hazards he will encounter; ability to overcome them.

The muskeg areas of northern Canada and the upper reaches of the Amazon are but two of the areas in which GSI is now effectively pioneering.

GSI welcomes the challenge of hitherto unexplored areas and those unsuccessfully explored. Its staff of engineers stands ready to design and supply the equipment and technical know-how . . . the field personnel to carry through. Call in GSI.